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STARPOWER

The U.S. and the International Quest For Fusion Energy

CONGRESS OF THE UNITED STATES
Office of Technology Assessment
Washington, DC 20510-8025

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Foreword

Fusion research, offering the hope of an energy technology with an essentially unlimited supply of fuel and relatively attractive environmental impacts, has been conducted worldwide for over three decades. In the United States, increased budgetary pressures, along with a decreased sense of urgency, have sharpened the competition for funding between one research program and another and between energy research programs and other components of the Federal budget. This report, requested by the House Committee on Science, Space, and Technology and endorsed by the Senate Committee on Energy and Natural Resources, reviews the status of magnetic confinement fusion research and compares its progress with the requirements for development of a useful energy technology. The report does not analyze inertial confinement fusion research, which is overseen by the House and Senate Armed Services Committees.

OTA analyzed the magnetic fusion research program in three ways: (1) as an energy program, by identifying important features of the technology and discussing its possible role in the energy supply mix; (2) as a research program, by discussing its role in training scientists and developing new fields of science and technology; and (3) as an international program, by reviewing its history of international cooperation and its prospects for even more extensive collaboration in the future.

OTA could not have conducted this work without the valuable assistance it received from many organizations and individuals. In particular, we would like to thank the advisory panel members, workshop participants, and outside reviewers, who provided guidance and extensive critical reviews to ensure the accuracy of the report. Responsibility for the final report, however, rests solely with the Office of Technology Assessment.

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NOTE: OTA appreciates and is grateful for the valuable assistance and thoughtful critiques provided by the advisory panel members. The panel does not, however, necessarily approve, disapprove, or endorse this report. OTA assumes full responsibility for the report and the accuracy of its contents.

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Executive Summary

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Chapter 1

Executive Summary

OVERVIEW

Potential Role of Fusion

If successfully developed, nuclear fusion could provide humanity with an effectively unlimited source of electricity that has environmental and safety advantages over other electric energy technologies. However, it is too early to tell whether these advantages, which could be significant, can be economically realized. **Research aimed at developing fusion as an energy source has been vigorously pursued since the 1950s, and, despite considerable progress in recent years, it appears that at least three decades of additional research and development will be required before a prototype commercial fusion reactor can be demonstrated.**

The Policy Context

The budget for fusion research increased more than tenfold in the 1970s, due largely to growing public concern about environmental protection and uncertainty in long-range energy supply. However, a much-reduced sense of public urgency in the 1980s, coupled with the mounting Federal budget deficit, halted and then reversed the growth of the fusion budget. Today, the fusion program is being funded (in 1986 dollars) at about half of its peak level of a decade ago (see figures 1-1 and 1-2).

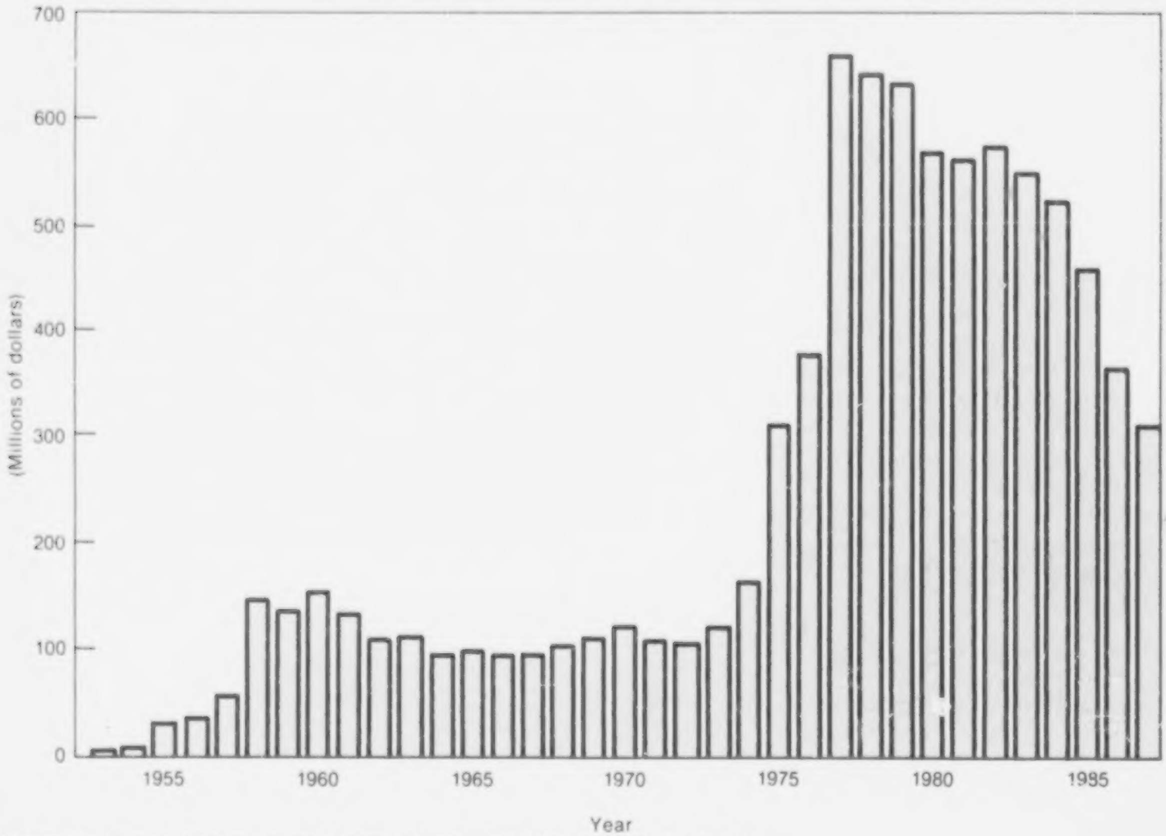
The change in the fusion program's status over the past 10 years has not resulted from poor technical performance or a more pessimistic evaluation of fusion's prospects. On the contrary, the program has made substantial progress. However, the disappearance of a perceived need for near-term commercialization has reduced the impetus to develop commercial fusion energy and has tightened pressure on fusion research budgets. Over the past decade, the fusion program has been unable to maintain a constant funding level, much less command the substantial funding increases required for next-generation facilities. In fact, due to funding constraints, the program has been unable to complete and operate some of its existing facilities.

The Department of Energy (DOE) manages the U.S. fusion program, and its goal is to evaluate fusion's technological feasibility—to determine whether or not a fusion reactor can be designed and built—early in the 21st century. A positive evaluation would enable a decision to be made at that time to construct a prototype commercial reactor. **However, this schedule cannot be met under existing U.S. fusion budgets. The DOE plan requires either that U.S. budgets be increased substantially or that the world fusion programs collaborate much more closely on fusion research.**

Choices made over the next several years can place the U.S. fusion program on one of four fundamentally different paths, which are discussed more thoroughly in chapter 8 of this report:

1. With substantial funding increases, the fusion program could complete its currently mapped-out research effort domestically, permitting decisions to be made early in the next century concerning fusion's potential for commercialization.
2. At only moderate increases in U.S. funding levels, the same results as above might be attainable—although possibly somewhat delayed—if the United States can work with some or all of the world's other major fusion programs (Western Europe, Japan, and the Soviet Union) at an unprecedented level of collaboration.
3. Decreased funding levels, or current funding levels in the absence of extensive collaboration, would require modification of the program's overall goals. At these constrained funding levels, U.S. evaluation of fusion as an energy technology would be delayed.

Figure 1-1.—Historical Magnetic Fusion R&D Funding, 1951-87 (in 1986 dollars)



SOURCE: U.S. Department of Energy, Office of Energy Research, letter to OTA project staff, Aug. 15, 1986.

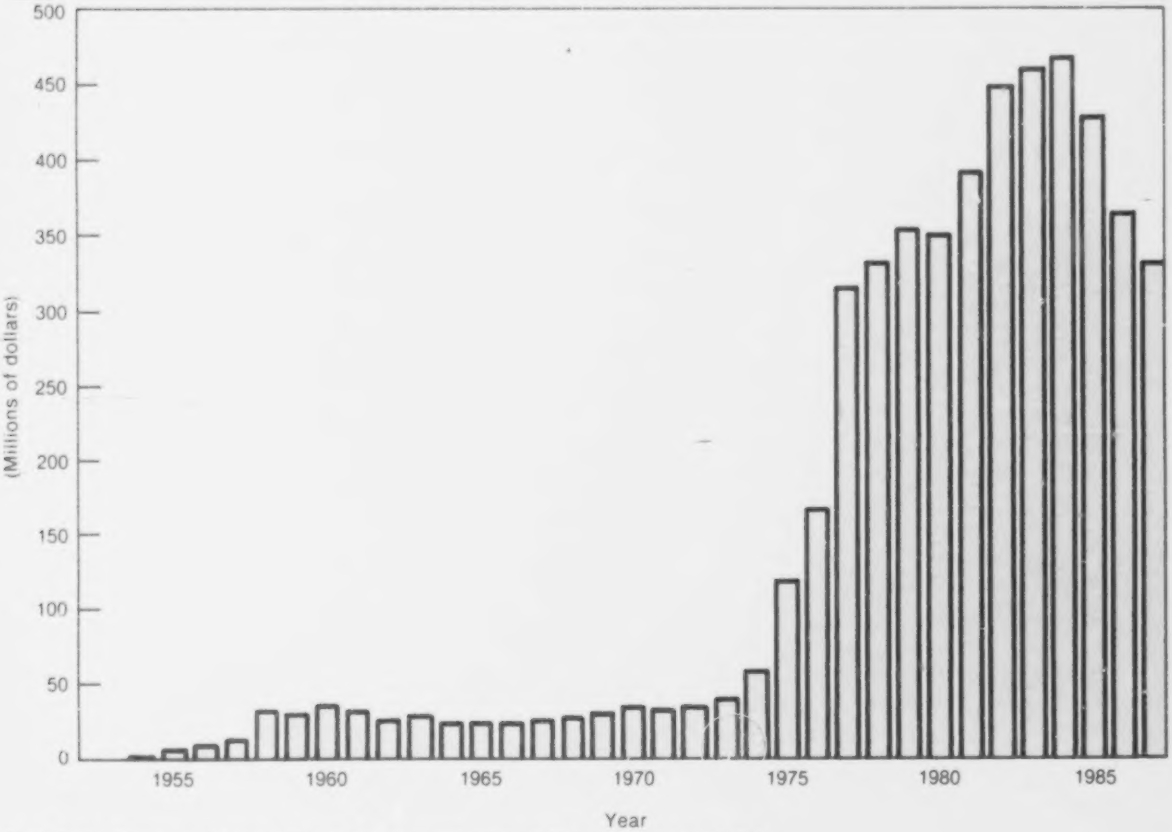
4. If fusion research ceased in the United States, the possibility of domestically developing fusion as an energy technology would be foreclosed unless and until funding were restored. Work would probably continue abroad, although possibly at a reduced pace; resumption of research at a later time in the United States would be possible but difficult.

Findings

Here are some of the overall findings from OTA's analysis:

- Experiments now built or proposed should, over the next few years, resolve most of the major remaining scientific uncertainties regarding the fusion process. If those experiments do not uncover major surprises, it is likely—although by no means certain—that the engineering work necessary to build an electricity-producing fusion reactor can be completed successfully.
- Additional scientific understanding and technological development is required before fusion's potential can be assessed. It will take at least 20 years, under the best circumstances, to determine whether construction of a prototype commercial fusion reactor will be possible or desirable; additional time beyond then will be required to build, operate, and evaluate such a device.
- It is now too early to tell whether fusion reactors, once developed, can be economically competitive with other energy technologies.

Figure 1-2.—Historical Magnetic Fusion R&D Funding, 1951-87 (in current dollars)



SOURCE U.S. Department of Energy, Office of Energy Research, letter to OTA project staff, Aug. 15, 1986

- Demonstration and commercialization of fusion power will take several decades after completion of the research program. Even under the most favorable circumstances, it does not appear likely that fusion will be able to satisfy a significant fraction of the Nation's electricity demand before the middle of the 21st century.

- With appropriate design, fusion reactors could be environmentally superior to other nuclear and fossil energy production technologies. Unlike fossil fuel combustion, fusion reactors do not produce carbon dioxide gas, whose accumulation in the atmosphere could affect world climate. Unlike nuclear fission—the process utilized in existing nuclear powerplants—fusion reactors should not produce high-level, long-lived radioactive wastes.
- One of the most attractive features of fusion is its essentially unlimited fuel supply. The only resources possibly constraining fusion's development might be the materials needed to build fusion reactors. At this stage of development, it is impossible to determine what materials will eventually be developed and selected for fusion reactor construction.
- If fusion technology is developed successfully, it should be possible to design fusion reactors with a higher degree of safety assurance than fission reactors. It may be possible to design fusion reactors that are incapable of causing any immediate off-site fatalities in the event of malfunction, natural disaster, or operator error.

- Potential problems with other major sources of electricity—fossil fuels and nuclear fission—provide incentives to develop alternate energy technologies as well as to substantially improve the efficiency of energy use. Fusion is one of several technologies being explored.
- It is unlikely that major, irreversible energy shortages will occur early in the next century that could only be ameliorated by the crash development of fusion power. There is little to be gained—and a great deal to be lost—by introducing fusion before its potential economic, environmental, and safety capabilities are attained. Even if difficulties with other energy technologies are encountered that call for the urgent development of an alternative source of energy supply, that alternative must be preferable in order to be accepted. It would be unwise to emphasize one fusion feature—economics or safety or environmental advantages—over the others before we know which aspect will be most important for fusion's eventual acceptance.
- Due to the high risk and the long time before any return can be expected, private industry has not invested appreciably in fusion research and cannot be expected to do so in the near future. But, unless the government decides to own and operate fusion generating stations, the responsibility for fusion research, development, and commercialization must be transferred to private industry at some stage. The nature and timing of this transition are highly controversial.
- Fusion research has provided a number of near-term benefits such as development of plasma physics, education of trained researchers, contribution to "spin-off" technologies, and support of the scientific stature of the United States. However, fusion's contributions to these areas do not imply that devoting the same resources to other fields of study would not produce equivalent benefits. Therefore, while near-term benefits do provide additional justification for conducting research, it is difficult to use them to justify one field of study over another.
- Fusion research has a long history of successful and mutually beneficial international cooperation. If this tradition can be extrapolated in the future to an unprecedented level of collaboration, much of the remaining cost of developing fusion power can be shared among the world's major fusion programs.
- International collaboration cannot substitute for a strong domestic research program. If the domestic program is sacrificed to support international projects, the rationale for collaboration will be lost and the ability to conduct it successfully will be compromised.
- Agreeing to collaborate on fusion research, both within the U.S. Government and between the U.S. Government and potential partners, will require sustained support at the highest levels of government. A variety of potential difficulties associated with large-scale collaborative projects will have to be resolved, and Presidential support will be required. If these difficulties can be resolved, the benefits of successful collaboration are substantial.

A QUICK FUSION PRIMER

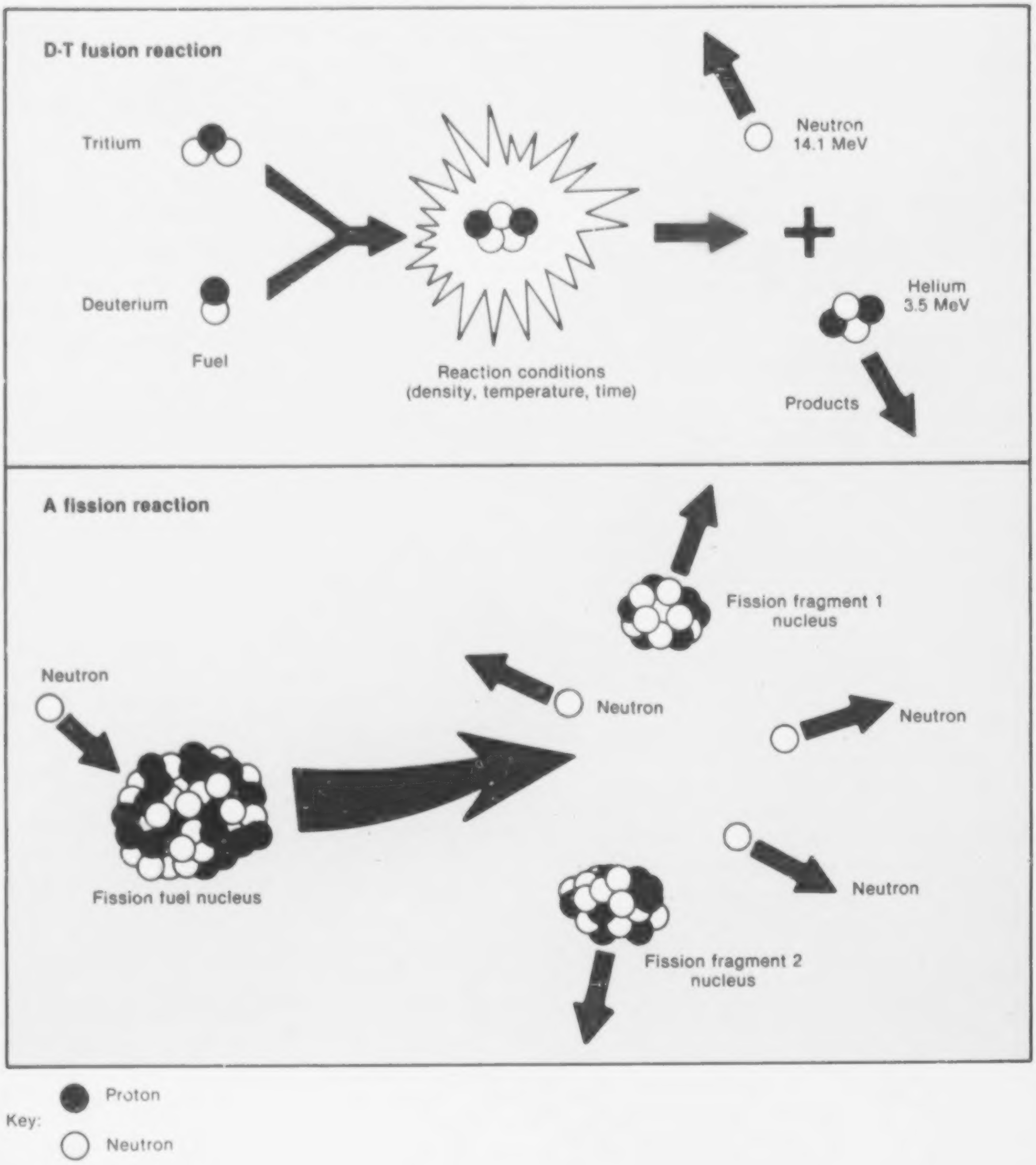
The Fusion Reaction

In a fusion reaction, the nuclei—or central cores—of light atoms combine or fuse together; when they do, energy is released. In a sense, fusion is the opposite of *fission*, the process utilized in existing nuclear powerplants (see figure 1-3), in which energy is released when a heavy nucleus splits into smaller pieces.

The lightest atom, hydrogen, is the easiest one to use for fusion. Hydrogen has three forms, or isotopes; two of them—deuterium (D) and tritium (T)—in combination work the best in fusion reactions. The kinetic energy released in the D-T reaction can be converted to heat, which in turn can be used to make steam to drive a turbine to generate electricity.

But a fusion reaction cannot happen unless certain conditions are met. To fuse hydrogen nuclei together, the nuclei must be heated to approximately 100 million degrees Celsius (C). At these

Figure 1-3.—The D-T Fusion Reaction and a Fission Reaction


D-T fusion reaction
Tritium
Deuterium
Fuel
Reaction conditions
(density, temperature, time)
Neutron
14.1 MeV
+
Helium
3.5 MeV
Products
A fission reaction
Neutron
Fission fuel nucleus
Fission fragment 1
nucleus
Neutron
Neutron
Neutron
Fission fragment 2
nucleus
Key:
Proton
Neutron

MeV: million electron volts

SOURCE: Adapted from Princeton Plasma Physics Laboratory, Information Bulletin NT-1: Fusion Power, 1984, p. 2; Office of Technology Assessment (fission), 1987.

temperatures, matter exists as *plasma*, a state in which atoms are broken down into electrons and nuclei. Keeping a plasma hot enough for a long enough period of time, and effectively confining it, are crucial for generating fusion power.

While no solid container can withstand the heat of a plasma, magnetic fields may be able to confine a plasma successfully. This assessment discusses *magnetic confinement* research and the various magnetic field configurations that look promising for producing fusion power.

More detail on the basics of fusion power can be found in chapter 2.

The Feasibility of Fusion

Before fusion powerplants can generate electricity, fusion must be proven technologically and commmercially feasible.

Technological feasibility will require that both *scientific feasibility* and *engineering feasibility* be shown. Scientists must bring fusion reactions to *breakeven*, the point at which at least as much energy is produced as must be input to maintain the reaction. Existing experiments are expected to reach this long-elusive milestone by 1990. Beyond breakeven, scientists have an even harder but more important task of creating *high energy gain*—energy output that is many times higher than the energy input. Only when high-gain reactions are produced will the scientific feasibility of the fusion process be demonstrated. If a high-gain reaction reaches *ignition*, it will sustain itself even when the external heat is turned off.

Once scientific feasibility of fusion as a potential energy source is established, the engineering development necessary to develop fusion reactors must be completed. Engineering feasibility denotes the successful development of reliable components, systems, and subsystems for operating fusion reactors.

Scientific and engineering feasibility, although involving different issues, are interdependent. Demonstrating either one will require advances to be made in basic scientific understanding as well as in technological capability.

The goal of fusion research is to prove fusion's technological feasibility so that its commercial feasibility is likely. To be marketable, fusion power must be socially and environmentally acceptable and economically attractive compared to its competitors, and it must meet regulatory and licensing requirements.

Probability of Success

Experiments now existing or proposed to be built should be sufficient, within the next few years, to demonstrate fusion's scientific feasibility. If these experiments do not uncover unfavorable surprises, it appears likely—although not certain—that fusion's engineering feasibility can be subsequently established. Most of the technological and engineering challenges to designing and building a reactor have been identified. **However, it cannot yet be determined whether or not a fusion reactor will be commercially attractive.**

HISTORY OF MAGNETIC CONFINEMENT FUSION RESEARCH

1950s and 1960s

From 1951 until 1958, fusion research was conducted by the U.S. Atomic Energy Commission (AEC) in a secret program code-named "Project Sherwood." Many different magnetic confinement concepts were explored during the early 1950s. Although researchers were careful to note that practical applications lay at least 10 to 20 years in the future, the devices being studied were thought to be capable of leading directly to a commercial reactor.

In reality, however, very little was known about the behavior of plasma in experiments and even less about how it would act under the conditions required for fusion reactors. Experimental results were often ambiguous or misinterpreted, and the theoretical understanding underlying the research was not well established. By 1958—as people

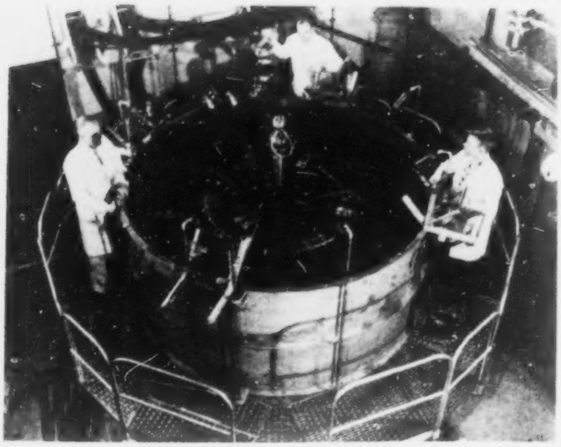


Photo credit: Los Alamos National Laboratory

Perhapsatron, built and operated in the 1950s at Los Alamos Scientific Laboratory.

realized that harnessing magnetic fusion was going to be difficult and that national security considerations were less immediate—the research was declassified. This action made widespread international cooperation in fusion research possible, particularly since the countries involved realized that the state of their research programs was more or less equivalent.

With the optimism of the 1950s tempered, fusion researchers in the United States proceeded at a steady pace throughout the 1960s. In 1968, Soviet scientists announced a major breakthrough in plasma confinement in a device called a "tokamak." After verifying Soviet results, the other world fusion programs redirected their efforts toward development of the tokamak.

1970s and 1980s

With the identification of the tokamak as a confinement concept likely to reach reactor-level conditions, the U.S. fusion program grew rapidly. Between 1972 and 1979, the fusion program's budget increased more than tenfold. This growth was due in part to uncertainty in the early 1970s concerning long-range energy supply; fusion energy, with its potentially inexhaustible fuel supply, appeared to be an attractive alternative to exhaustible resources such as oil and gas. In addition, the growth of the environmental movement and increasing opposition to nuclear fission technology drew public support to fusion as an energy technology that might prove more environmentally acceptable than other energy technologies.

The fusion program capitalized on this public support; program leadership placed a high priority on developing a research plan that could lead to a demonstration reactor. Planning began for the Tokamak Fusion Test Reactor, a new experiment using D-T fuel that would reach breakeven. By 1974, the funding increases necessary to pursue accelerated development of fusion were appropriated.

Program organization changed twice during the 1970s. In 1974, Congress abolished the AEC and transferred its energy research programs to the newly created Energy Research and Development Administration (ERDA). ERDA assumed management of the AEC's nuclear fission and fusion programs, as well as programs in solar and renewable technologies, fossil fuels, and conservation. Three years later, President Carter incorporated the functions of ERDA into a new agency, the Department of Energy (DOE).

Under DOE, the fusion program did not have the same sense of urgency. Fusion could not mitigate the short-term oil and gas crisis facing the United States. Furthermore, as a potentially inexhaustible energy source (along with solar energy and the fission breeder reactor), fusion was not expected to be needed until well into the next century. Therefore, there appeared to be no compelling reasons to rapidly develop a fusion demonstration plant.

Nevertheless, the Magnetic Fusion Energy Engineering Act of 1980 urged acceleration of the national effort in magnetic fusion research, development, and demonstration activities. The act recommended that funding levels for magnetic fusion double (in constant dollars) within 7 years. However, Congress did not appropriate these increases, and there was no follow-up. Actual appropriations in the 1980s have not grown at the levels specified in the act; in fact, since 1977, they have continued to drop in constant dollars.

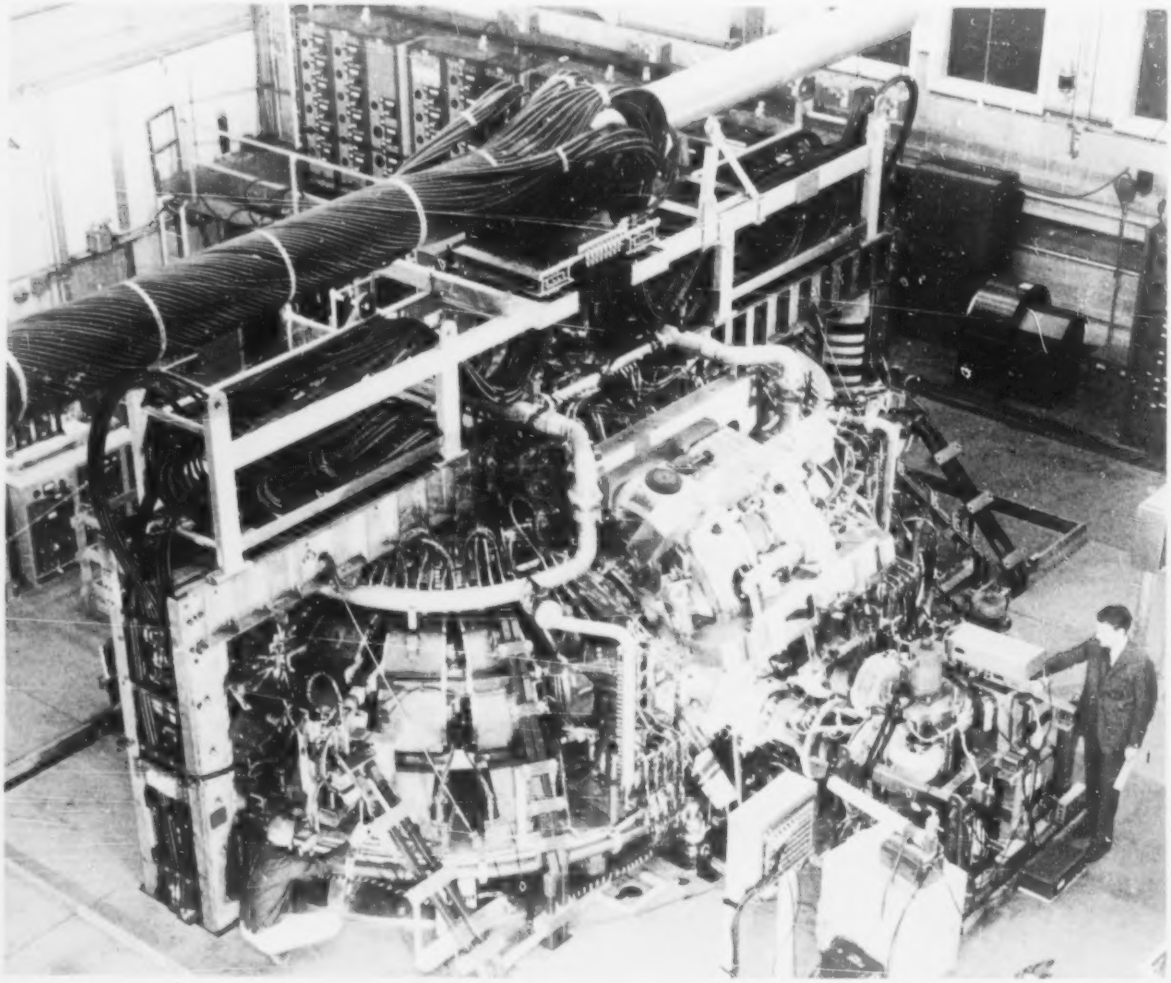


Photo credit: Princeton Plasma Physics Laboratory

Model C Stellarator at Princeton Plasma Physics Laboratory. Designed and built in the late 1950s, the Model C was converted into the United States' first tokamak in 1970.

Despite constrained funding, the U.S. fusion program has made significant advances in plasma physics and fusion technology throughout the 1980s. However, DOE has had to adjust its long-range planning to the new fiscal situation. In 1985, it issued the Magnetic Fusion Program Plan (MFPP), which states that the goal of the fusion program is to establish the scientific and technological base required for fusion energy. This plan explicitly recognizes that:

> . . . although the need for and desirability of an energy supply system based on the nuclear fusion principle have not diminished, there is less urgency to develop such a system.[1]

The plan emphasizes the importance of international collaboration if the United States is to establish fusion's technological feasibility during the early 21st century.

The history of U.S. magnetic confinement fusion research is discussed in chapter 3 of this report.

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[1] U.S. Department of Energy, Office of Energy Research, *Magnetic Fusion Program Plan*, DOE/ER-0214, February 1985, preface.

FUSION SCIENCE AND TECHNOLOGY

Great scientific progress has been made in the field of fusion research over the past 35 years. The fusion program appears to be within a few years of demonstrating breakeven, an event that will show an impressive degree of understanding and technical capability. Nevertheless, many scientific and technological issues must be resolved before fusion reactors can be designed and built. The principal scientific uncertainties involve what happens to a plasma when it generates appreciable amounts of fusion power. Because no existing devices can produce significant amounts of power, this uncertainty currently cannot be explored. Simply reaching breakeven will not resolve the uncertainties, since the effects of internally generating fusion power will not be fully realized under breakeven conditions. An ignited plasma, or at least one with high energy gain, must be studied. Issues to be resolved before fusion's technological feasibility can be established are discussed more fully in chapter 4.

Confinement Concepts

Besides the behavior of ignited plasmas, the characteristics, advantages, and disadvantages of various confinement concepts need further study. Several different concepts, utilizing different configurations of magnetic fields and different methods of generating the fields, are being studied (table 1-1).

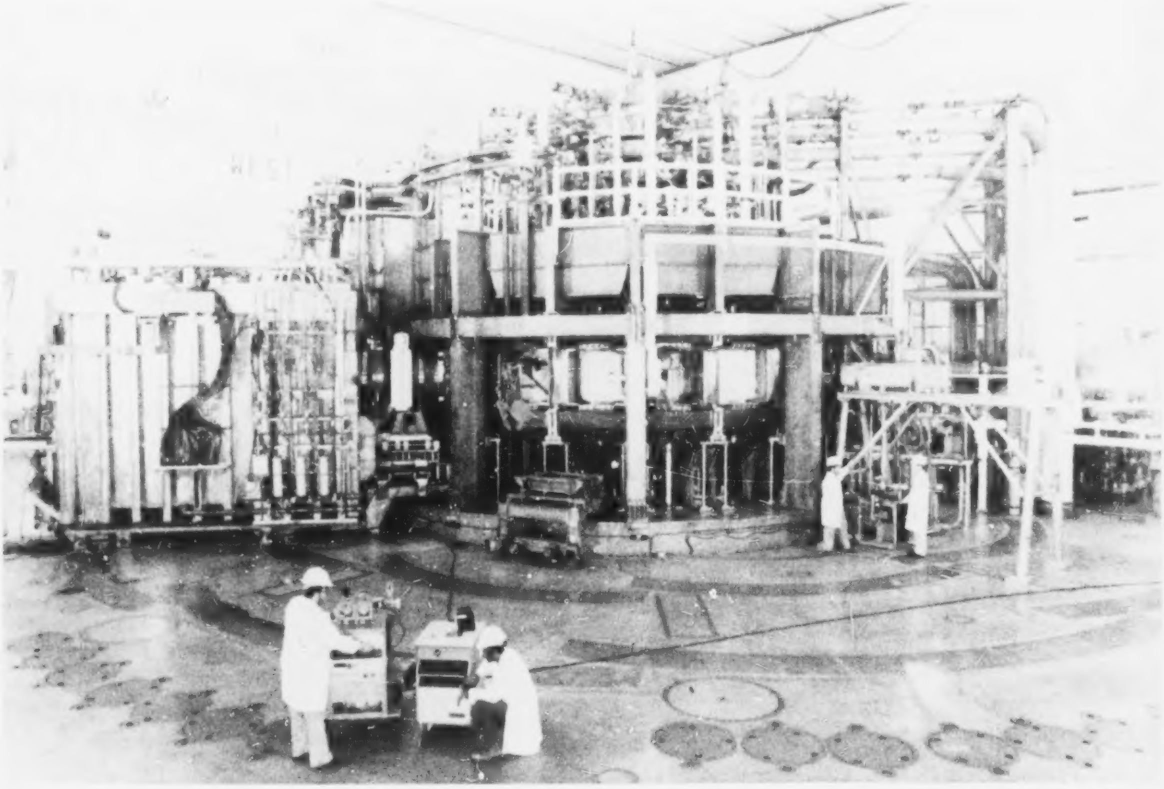


Photo credit: Princeton Plasma Physics Laboratory

The Tokamak Fusion Test Reactor at Princeton Plasma Physics Laboratory, where breakeven experiments are scheduled for 1990.

Table 1-1.—Classification of Confinement Concepts

Well-developed knowledge base	Moderately developed knowledge base	Developing knowledge base
Conventional Tokamak	Advanced Tokamak Tandem Mirror Stellarator Reversed-Field Pinch	Spheromak Field-Reversed Configuration Dense Z-Pinch

SOURCE: Adapted from Argonne National Laboratory, Fusion Power Program, *Technical Planning Activity: Final Report*, commissioned by the U.S. Department of Energy, Office of Fusion Energy, ANL/FPP-87-1, 1987, p. 15.

At this stage of the research program, it is not known which confinement concepts can form the basis of an attractive fusion reactor. The tokamak is the most developed concept, and it has attained plasma conditions closest to those required in a fusion reactor. Its experimental performance has been encouraging, and it provides a standard for comparison to other concepts. Studies of reactor-like plasmas must be done in tokamaks because no other concept has yet demonstrated the potential to reach reactor conditions. Most fusion technology development takes place in tokamaks as well. Although tokamak behavior has not yet been fully explained theoretically, it may well be possible to design reactor-scale tokamaks on the basis of experimental performance in smaller tokamaks.

Research on alternatives to the tokamak continues because it is not clear that the tokamak will result in the most attractive or acceptable fusion reactor. Moreover, research conducted on different concepts provides important insights into the fusion process. It remains to be seen which alternate concepts will be able to reach the level of performance already attained by the tokamak, whether their relative strengths will be preserved in the development process, and what the costs of developing these concepts to reactor scale will be. Nor is it known what the ultimate capability of the tokamak concept will be.

Reactor Development

Just as an automobile is much more than spark plugs and cylinders, a fusion reactor will contain many systems besides those that heat and confine the plasma. Fusion's overall feasibility will depend on all of the "engineering details" that support the fusion reaction, convert the power released in the reaction into usable energy, and ensure safe, environmentally acceptable operation. Developing and building these associated systems and integrating them into a reactor will require a technological development effort at least as impressive as the scientific challenge of understanding and confining fusion plasmas.

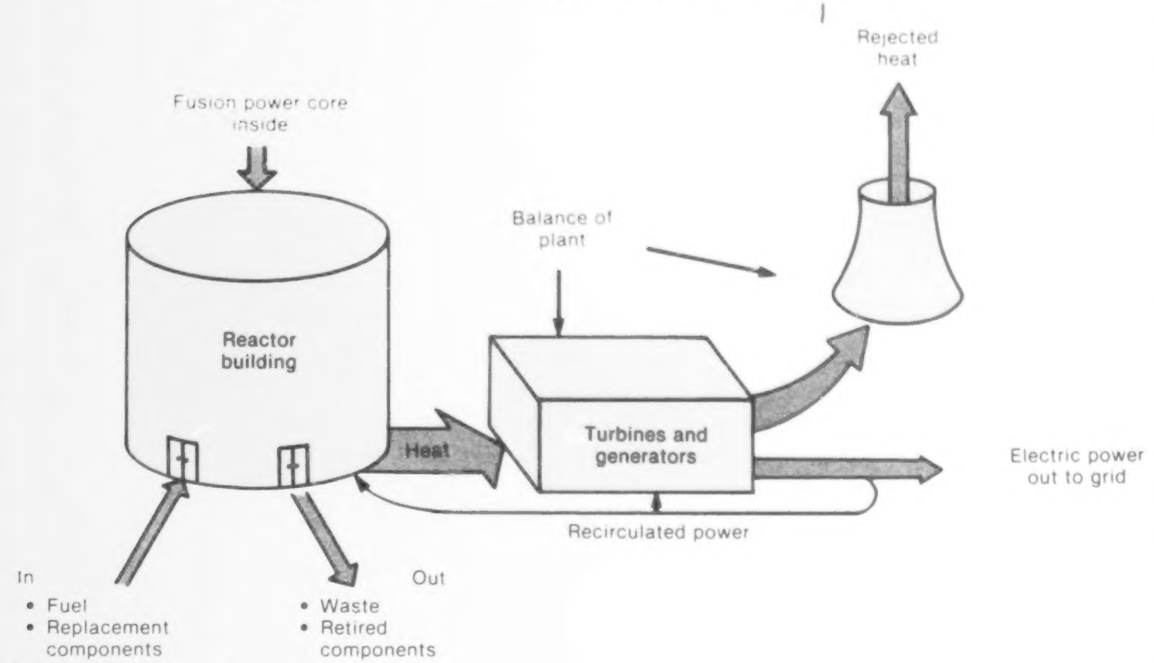
The overall fusion generating station (figure 1-4) consists of a *fusion power core*, which contains the systems that support and recover energy from the fusion reaction, and the *balance of plant*, which converts this energy to electricity. Fusion reactor conceptual designs typically have balance of plant systems similar to those found in existing electricity generating stations. However, fusion technology may permit more advanced systems to generate electricity in a manner that is qualitatively different from the methods in use today.

The fusion power core, shown schematically in figure 1-5, is the heart of a fusion generating station. The systems in the core create and maintain the plasma conditions required for fusion reactions to occur. These technologies confine the plasma, heat and fuel it, remove wastes and impurities, and, in some cases, drive electric currents within the plasma. Other systems in the fusion power core recover heat from the fusion reactions, breed fuel, and provide shielding. One of the key requirements for many of these fusion power core systems is the development of suitable materials that are resistant to the intense neutron radiation generated by the plasma. The environmental and safety aspects of fusion reactors depend significantly on materials choice.

Future Plans and Facilities

Many additional experiments and facilities will be required to investigate both scientific and technological aspects of fusion. Preliminary experiments that investigate the basic characteristics of

Figure 1-4.—Systems in a Fusion Electric Generating Station



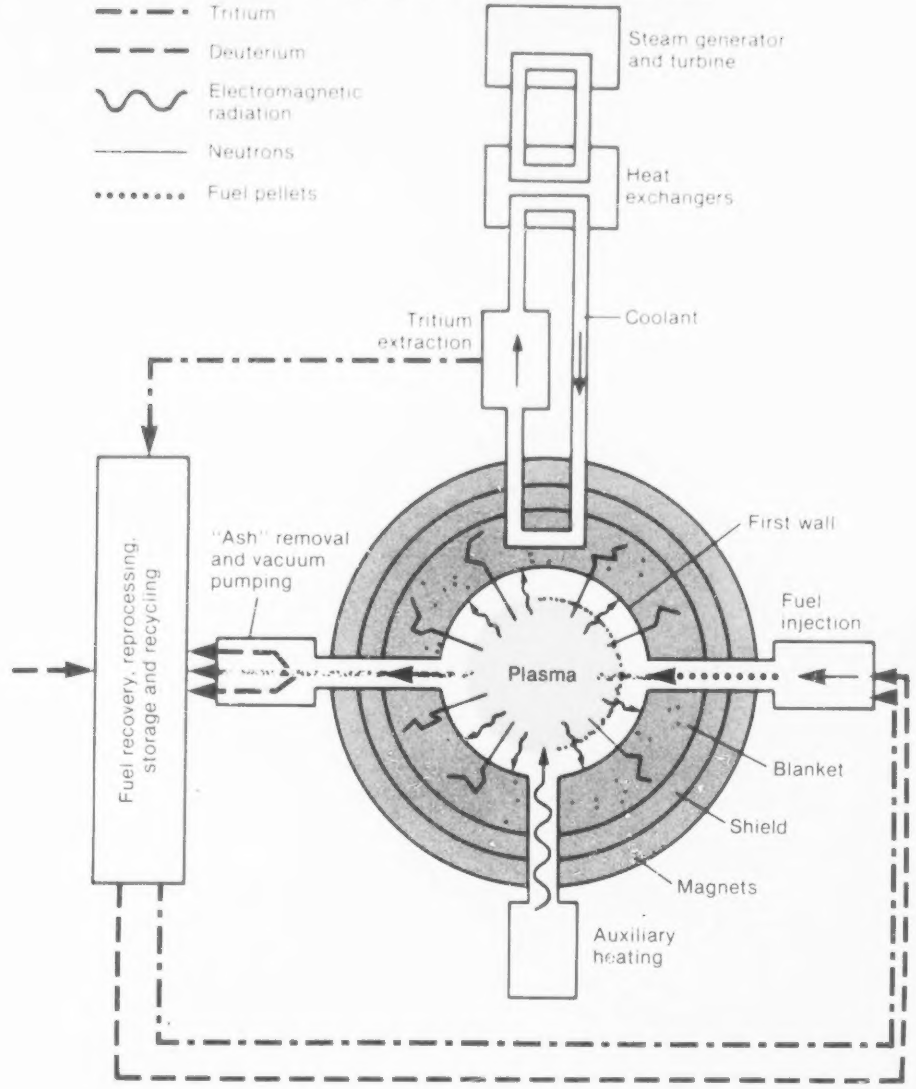
SOURCE: Office of Technology Assessment, 1987

new confinement concepts can be done for a few million dollars or less. As concepts approach reactor capability, successively larger facilities are required, with reactor-scale experiments costing hundreds of millions of dollars each. Obviously, the U.S. fusion program cannot afford to investigate every confinement concept at the reactor scale; choices must be made on the basis of information gathered at earlier stages.

Additional facilities will be required to resolve general issues not identified with specific confinement concepts. In particular, facilities will be needed to address the scientific issues associated with ignited plasmas. Many physical processes associated with ignition can be studied in ignited plasmas that only last for a few seconds; other aspects, such as fueling and removal of reaction products, will require a facility that can produce ignited plasmas lasting hundreds of seconds. Short- and long-burn ignition questions can be studied either in a single device or in two separate devices. DOE has chosen to separate them, and it has requested funds in its 1988 budget to build a short-pulse ignition facility, called the Compact Ignition Tokamak (CIT). Total costs for this device are estimated at about $360 million.

CIT cannot satisfy the requirements for long pulses, materials studies, or nuclear technology testing. These needs could be addressed in separate facilities and later combined (except for materials testing) in a device that would integrate all the systems for the first time. Alternatively, many of these issues could be addressed and integrated simultaneously in a next-generation engineering test reactor. Satisfying a number of purposes simultaneously would complicate an engineering test reactor's design and could force trade-offs between the different objectives. Moreover, it is likely that each additional requirement will increase the price of the machine. Even so, a general-purpose engineering test reactor would presumably cost less than the combination of several single-purpose facilities and a subsequent system-integration device.

Figure 1-5.—Systems in the Fusion Power Core


Tritium
Deuterium
Electromagnetic radiation
Neutrons
Fuel pellets
Steam generator and turbine
Heat exchangers
Tritium extraction
Coolant
Fuel recovery, reprocessing, storage and recycling
"Ash" removal and vacuum pumping
First wall
Fuel injection
Plasma
Blanket
Shield
Magnets
Auxiliary heating

SOURCE: Modified from "The Engineering of Magnetic Fusion Reactors," by Robert W. Conn. Copyright © 1983 by Scientific American, Inc. All rights reserved.

DOE has not yet determined the features to be included in an engineering test reactor. It is committed to investigating the possibility for international cooperation on the device; the U.S. Government has proposed to the other major world fusion programs that collaborative conceptual design of such a device, called the International Thermonuclear Experimental Reactor (ITER), be undertaken.

Materials testing will require a dedicated device even if a general-purpose engineering test reactor is built. To complete lifetime irradiation testing of reactor materials in a reasonable

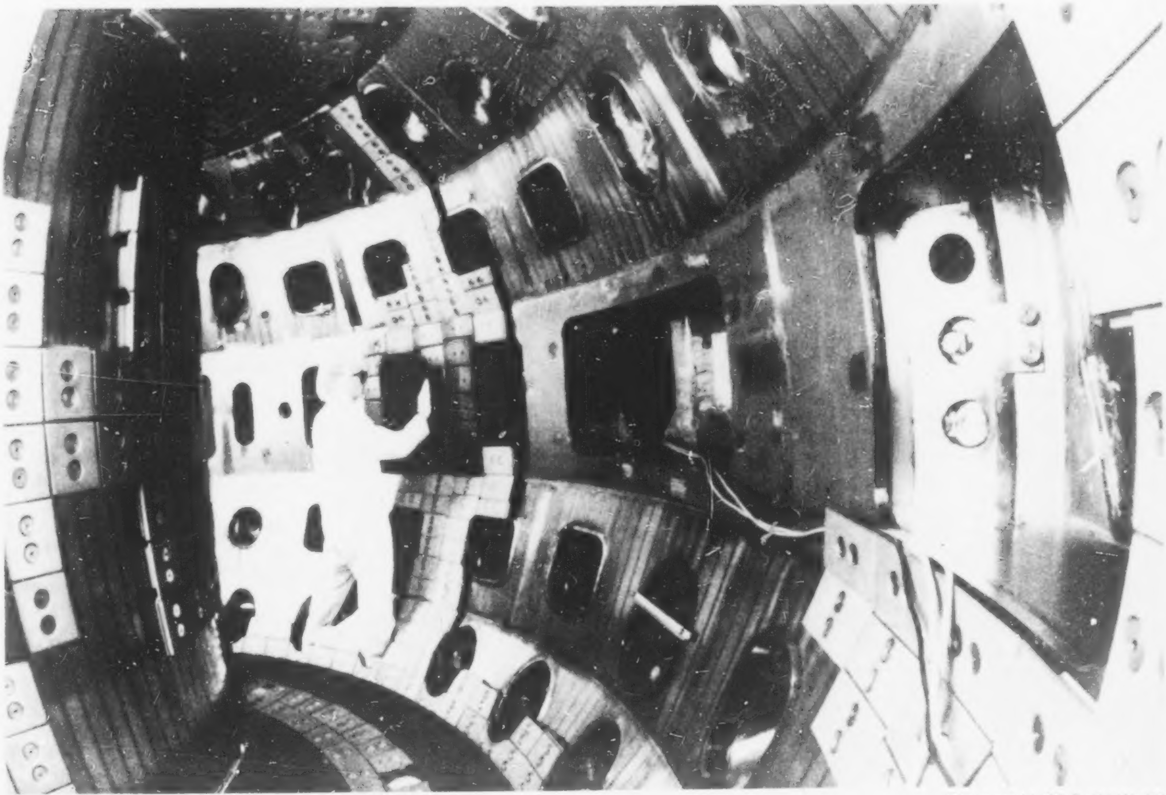


Photo credit: GA Technologies

View inside vacuum vessel of D III-D fusion device at GA Technologies, San Diego, CA. The plasma is contained within this vessel.

amount of time, a source of fusion neutrons several times more intense than expected from a commercial reactor is required. While an engineering test reactor would duplicate conditions expected in a reactor, it would not be able to conduct accelerated materials tests at several times the radiation levels to be found in a reactor.

Schedules and Budgets

A major fusion-communitywide study has identified the technical tasks and facilities required to establish fusion's technological feasibility and enable a decision to be made early in the next century to start the commercialization process.[2] The study estimated that the worldwide cost of this research effort would be about $20 billion. As mentioned earlier, developing fusion on this schedule will require either substantially increased U.S. funding or wide-scale collaboration among the world fusion programs.

The requirements and schedule for establishing fusion's subsequent commercial feasibility are more difficult to project, and they depend on factors other than fusion research funding. Conceivably, if the research program provides the information necessary to design and build a reactor prototype, such a device could be started early in the next century. After several years of construction and several more years of qualification and operation, a base of operating experience could be acquired that would be sufficient for the design and construction of commercial devices.

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[2] Argonne National Laboratory, Fusion Power Program, *Technical Planning Activity: Final Report*, commissioned by DOE, Office of Fusion Energy (OFE), ANL/FPP-87-1, 1987.

If the regulatory and licensing process proceeded concurrently, vendors and users could begin to consider manufacture and sale of commercial fusion reactors sometime during the middle of the first half of the next century. From that point, it will take decades for fusion to penetrate energy markets. **Even under the most favorable circumstances, it does not appear likely that fusion will be able to satisfy a significant fraction of the Nation's electricity demand before the middle of the 21st century.**

This schedule for demonstrating technological and commercial feasibility requires a number of assumptions. Sufficient financial support or international coordination must be attained so that the research needed to establish technological feasibility can be completed early in the next century. Research must proceed without major difficulty and must lead to a decision to build a reactor prototype. The prototype must operate as expected and prove convincingly that fusion is both feasible and preferable to its alternatives.

Status of the World Programs

The United States, Western Europe, Japan, and the Soviet Union all have major programs in fusion research that are at similar stages of development. Each program has built or is building a major tokamak experiment. The U.S. Tokamak Fusion Test Reactor and the European Community's Joint European Torus are operating and are ultimately intended to reach breakeven conditions with D-T fuel. Japan's JT-60 tokamak, also operational, will not use tritium fuel; it is intended to generate a "breakeven-equivalent" plasma using ordinary hydrogen and deuterium. The Soviet Union's T-15 experiment is under construction. In addition to these major devices, each of the programs operates several smaller fusion experiments that explore the tokamak and other confinement concepts. Each program is also developing other aspects of fusion technology.

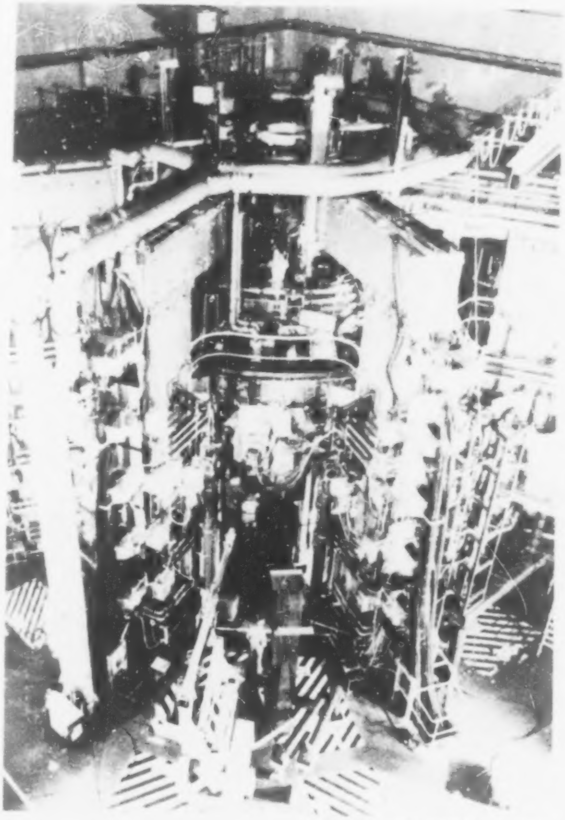

Photo credit: JET Joint Undertaking

The Joint European Torus, located in Abingdon, United Kingdom.

FUSION AS AN ENERGY PROGRAM

The long-term goal of the fusion program in the United States is to produce electricity. Fusion reactors can also produce fuel for fission reactors by irradiating suitable materials with neutrons, but this ability is not seen as fusion's primary application in the United States, Western Europe, or Japan. (The Soviet fusion effort does appear oriented towards producing fuel for fission reactors.)[3]

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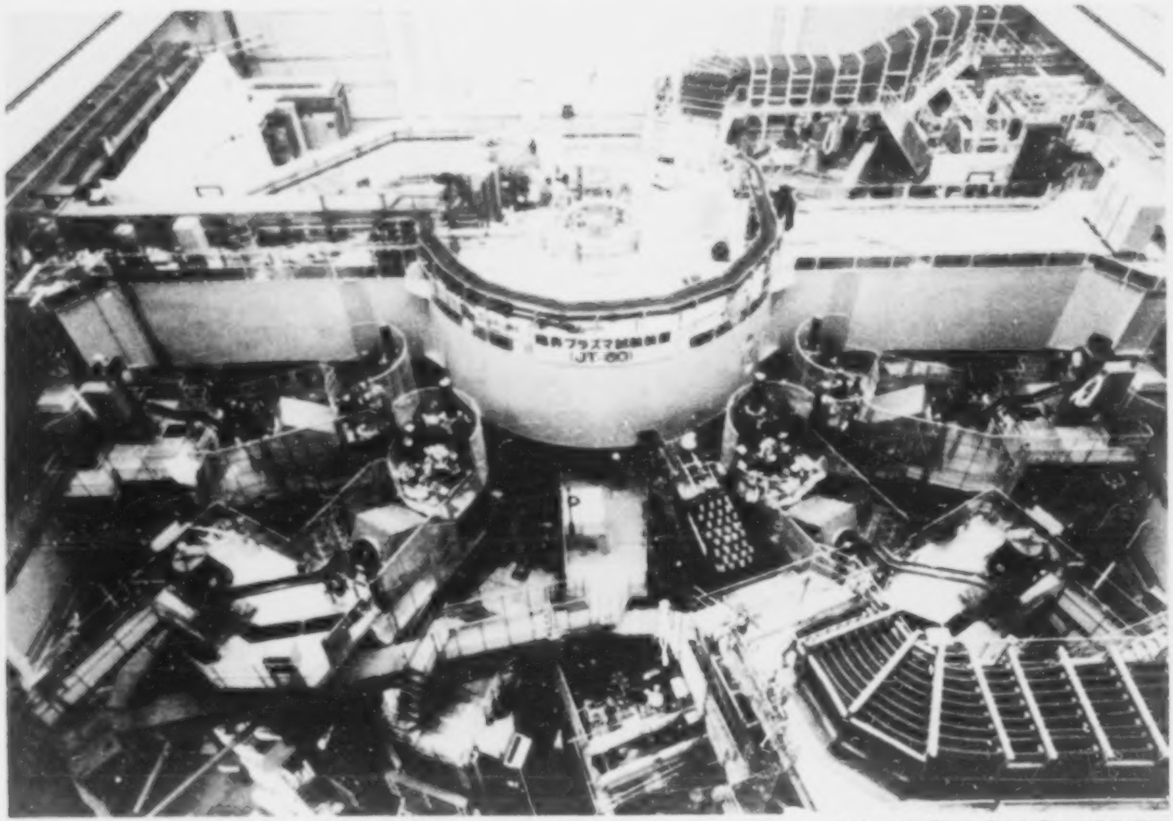
[3] A fusion reactor that produces fissionable fuel, or one that generates part of its energy from fission reactions that are induced by fusion-generated neutrons, is called a *fission/fusion hybrid* reactor. Although the applications and characteristics of hybrid reactors are different from those of "pure fusion" reactors that do not use or



Ph -dit: Japanese Atomic Energy Research Institute

The JT-60 tokamak, located in Naki-machi, Japan.

Hypothetical designs for fusion reactors that produce electricity have been studied for a number of years. Since the research program is far from complete, however, current systems studies are necessarily tentative. Although these studies have been especially valuable in identifying improvements in fusion physics or technology that appear to have the greatest potential for making fusion reactors attractive and competitive, they cannot provide a firm basis for assessing fusion's potential as a future energy source. Nevertheless, the studies do provide a basis for projecting the possible characteristics of fusion reactors. These projections will improve as additional knowledge and understanding enable scientists and engineers to better model the reactor systems. Chapter 5 of this report discusses projected characteristics of fusion reactors, along with the factors that will determine the degree to which fusion is accepted in the energy marketplace.

Safety

If fusion development is successful, it may be possible to ensure that accidents due to malfunctions, operator error, or natural disasters could not result in immediate public fatalities. This safety would depend on passive systems or on materials properties, rather than on active systems that could fail or be overridden. A number

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produce fissionable materials, there is little difference at present in the research required to develop the two. Differences will arise at subsequent stages of research and development.

This assessment focuses on pure fusion reactors; hybrid reactors are discussed briefly in app. A of the full report.

of attributes of the fusion process should make safety assurance easier for fusion reactors than for fission reactors:

- Fusion reactions cannot run away. Fuel will be continuously injected, and the amount contained inside the reactor chamber will only operate the reactor for a short period of time. Energy stored in the plasma at any given time can be dissipated by the vacuum chamber in which the fusion reactions take place.
- With appropriate choice of materials, the amount of heat produced by the decay of radioactive materials in the reactor after the reactor has been shut down should be less for fusion reactors than for fission reactors. Fusion reactors should therefore require simpler post-shutdown or emergency cooling systems, if any such systems are required at all.
- The radioactive inventory of a fusion reactor —in terms of both the total amount present in the reactor and the fraction that would be likely to be released in an accident—should be smaller than that of a fission reactor. Fusion will not generate long-lived wastes such as those produced by fission reactors. Except for tritium gas, the radioactive substances present in fusion reactors will generally be bound as metallic structural elements.
- In the event of accidental release, fusion reactors should not contain radioactive elements —except tritium—that would tend to be absorbed in biological systems. Tritium is an inherent potential hazard, but the risk it poses is much smaller than that of the gaseous or volatile radioactive byproducts present in fission reactors. Active tritium inventories in current fusion reactor designs are small enough that even their complete release should not produce any prompt fatalities off-site. Moreover, fusion reactors operating on advanced fuel cycles would not need tritium.

This discussion does not imply that fission reactors are unsafe. Indeed, efforts are underway to develop fission reactors whose safety does not depend on active safety systems. However, the potentially hazardous materials in fission reactors include fuels and byproducts that are inherent to the technology. While the tritium fuel required by a D-T fusion reactor is a potential hazard, the byproducts of fusion are not in themselves hazardous. Since there is much greater freedom to choose materials that minimize safety hazards for fusion reactors than there is in fission reactor design, a higher degree of safety assurance should be attainable with fusion.

Environmental Characteristics

Fusion reactors will not be free of radioactive wastes, although the wastes that they produce should be easier to dispose of than fission wastes. Fusion reactors will not generate the long-lived and highly radioactive wastes contained in the spent fuel rods of fission reactors. Fusion wastes may have a greater physical volume than fission wastes, but they should be substantially less radioactive and orders of magnitude less harmful. The amount of radioactive waste anticipated from different fusion designs ranges over several orders of magnitude because it depends on the choice of materials with which the reactor is made. Special materials that do not generate intense or long-lived radioactive wastes may be developed that would make it possible to substantially reduce the radioactive waste produced by a fusion reactor.

Nuclear Proliferation Potential

The ability of a fusion reactor to breed fissionable fuel could increase the risk of nuclear proliferation. Proliferation concerns relate to the possibility of constructing fission-based or atomic weapons. Although fusion reactors contain tritium, a material that could be used in principle to make thermonuclear weapons such as the hydrogen bomb, such weapons cannot be built by parties who do not already possess fission weapons.

A reactor deriving all its energy from fusion and producing only electricity would not contain materials usable in fission-based nuclear weapons, and it would be impossible to produce such materials by manipulating the reactor's normal fuel cycle. However, material usable in fission weapons could be produced by placing other materials inside the reactor and irradiating them with fusion neutrons. This procedure, in effect, would convert a pure fusion reactor into a fission/fusion hybrid reactor (see note 3, above). If such modifications to the reactor structure were easily detected or were extremely difficult and expensive, pure fusion reactors would be easier to safeguard against surreptitious production of nuclear weapons material than existing fission reactors, and fusion reactors would therefore pose less of a proliferation risk.

Resource Supplies

Shortage of fuels will not constrain fusion's prospects for the foreseeable future. Enough deuterium is contained in the earth's waters to satisfy energy needs through fusion for billions of years at present consumption rates. Domestic lithium supplies should offer thousands of years worth of fuel, with vastly greater amounts of potentially recoverable lithium contained in the oceans.

Materials required to build fusion reactors may pose more of a constraint on fusion's development than fuel supply, but at this stage of research it is impossible to determine what materials will eventually be developed and selected for fusion reactor construction. No particular materials other than the fuels appear at present to be indispensable for fusion reactors.

Cost

It is currently impossible to determine whether a fusion reactor, once developed, will be economically competitive with other energy technologies. The competitiveness of fusion power will depend not only on successful completion of the remaining research program but also on additional factors that are impossible to predict—e.g., plant licensability, construction time, and reliability, not to mention factors less directly related to fusion technology such as interest rates. Fusion's competitiveness will also depend on technical progress made with other energy technologies.

Fusion's Energy Context

The factors that influence how successfully fusion technology will compete against other energy technologies include how well its characteristics meet the requirements of potential customers (most likely electric utilities) and how well fusion compares to alternate electricity-generating technologies. A more detailed look at these factors makes a number of points clear:

- **The overall size and composition of electricity demand, by itself, should neither require nor eliminate fusion as a supply option.** Supplies of both coal and uranium appear adequate at reasonable prices to meet high future demand in the absence of fusion.[4] It will be overall economics and acceptability, rather than total demand or fuel availability, which will determine the mix of energy technologies.
- **It is unlikely that any one technology will take over the electricity supply market, barring major difficulties with the others.**
- **Potential problems with currently foreseen future sources of electricity provide incentives to develop alternate energy technologies and/or substantially improve the efficiency of energy use.** Combustion of coal releases carbon dioxide, whose accumulation in the atmosphere may affect world climate; this problem may make increased reliance on coal undesirable. Safety, nuclear waste, or nuclear proliferation concerns may continue to impair expansion of the nuclear fission option. **The urgency for developing fusion, therefore, depends on assumptions of the likelihood that existing energy technologies will prove undesirable in the future.**

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[4] Coal supplies are adequate to provide power for centuries at current rates of use. Uranium supplies should be available at a reasonable price until well into the next century without requiring either breeder reactors or reprocessing. Advanced, more efficient fission reactors could delay the need for breeders or reprocessing still further. With the use of breeders, uranium deposits become adequate for centuries.

- **There is little to be gained and a great deal to be lost if fusion is prematurely introduced without attaining its potential economic, environmental, and safety capabilities.** Even in a situation where problems with other energy technologies urgently call for development of an alternative source of supply, that alternative must be preferable in order to be accepted. It would be unwise to emphasize one fusion feature—economics or safety or environmental advantages—over the others before we know which aspect will be most important for fusion's eventual acceptance.

FUSION AS A RESEARCH PROGRAM

The ultimate objective of fusion research is to produce a commercially viable energy source. Yet, because the research program is exploring new realms of science and technology, it also provides near-term, non-energy benefits. These benefits fall in four major categories.

Near-Term Benefits

1. Development of Plasma Physics

Plasma physics as a branch of science began in the 1950s, driven by the needs of scientists working on controlled thermonuclear fusion and, later, by the needs of space science and exploration. The field of plasma physics has developed rapidly and has synthesized many areas of physics previously considered distinct disciplines. Magnetic fusion research funding is crucial to the continuation of plasma physics research; over half of all Federal plasma physics research is funded by the magnetic fusion program.

2. Educating Scientists

Educating scientists and engineers is one of the most widely acknowledged benefits of the fusion program. Over the last decade, DOE's magnetic fusion energy program has financed the education of most of the plasma physicists produced in the United States. DOE, through its magnetic fusion program, directly supports university fusion programs and provides 37 fusion fellowships annually to qualified doctoral students. Training in plasma physics enables these scientists to contribute to defense applications, space and astrophysical plasma physics, materials science, applied mathematics, computer science, and other fields.

3. Advancing Science and Technology

Many high-technology research and development (R&D) programs produce secondary benefits or "spin-offs." Over the years, the magnetic fusion energy program has contributed to a variety of spin-off technologies with wide-ranging applications in other fields. Among them are superconducting magnet technology, high-quality vacuums, high-temperature materials, high-frequency and high-power radiofrequency waves, electronics, diagnostics and tools for scientific analysis, high-speed mainframe computers, and particle beams. Although spin-offs may benefit society, they are unanticipated results of research and should not be viewed as a rationale for continuing or modifying high-technology research programs. It is impossible to predict before-the-fact which research investments will have the greatest spin-off return.

4. Stature

The stature of the United States abroad benefits from conducting high-technology research. The United States has been at the forefront of fusion R&D since the program began in the 1950s. Maintaining a first-rate fusion program has placed the United States in a strong bargaining position when arranging international projects, has attracted top scientists from other fusion programs to the United States, and has enhanced the reputation of the United States in scientific and technical programs other than magnetic fusion.

Near-Term Financial and Personnel Needs

Financial Resources

The Federal R&D budget has grown steadily in the 1980s. The bulk of this growth has been driven by increases in defense spending, but nondefense R&D has also grown. The fraction of the Federal R&D budget devoted to energy, however, has been steadily declining during the 1980s. In fiscal year 1987, energy R&D is estimated to account for less than 4 percent of the Federal R&D budget.

Virtually all fusion research is funded by the Federal Government; due to fusion's long-term, high-risk nature, there is little private sector investment. Even though the fusion budget has fallen, in constant dollars, to less than half of its 1977 peak, magnetic fusion has fared better than many other energy programs. DOE's energy programs in nuclear fission, fossil fuels, conservation, and renewable energy technologies have lost proportionately more of their Federal support because it is believed that private sector financing is more appropriate in these cases. Figure 1-6 shows the budgets of DOE's larger energy R&D programs during the 1980s.

Personnel Resources

The fusion program currently supports approximately 850 scientists, 700 engineers, and 770 technicians.[5] These researchers work primarily at national laboratories and in university and college fusion programs. According to estimates by DOE, the number of Ph.D. staff positions in the fusion program has declined by almost 20 percent since 1983. Most of the fusion researchers who have left the fusion program have found work in other research programs within DOE and the Department of Defense. Many former fusion researchers, for example, are working on Strategic Defense Initiative projects.

Participation in the Magnetic Fusion Program

The Department of Energy's Office of Fusion Energy (OFE) conducts research through three different groups: national laboratories, colleges and universities, and private industry. Each of these groups has different characteristics, and each plays a unique role in the fusion program.

National Laboratories

It is estimated that national laboratories will conduct over 70 percent of the magnetic fusion R&D effort in fiscal year 1987. According to DOE, the laboratories are "a unique tool that the United States has available to carry on the kind of large science that is required to address certain problems in fusion."[6] Four laboratories conduct the bulk of the Nation's fusion research: Lawrence Livermore National Laboratory in Livermore, CA; Los Alamos National Laboratory in Los Alamos, NM; Oak Ridge National Laboratory in Oak Ridge, TN; and Princeton Plasma Physics Laboratory in Princeton, NJ.

Universities and Colleges

Within the fusion program, universities and colleges provide education and training and historically have been a major source of innovative ideas as well as scientific and technical advances. It is estimated that the university and college programs will receive about 11 percent of the Federal fusion budget directly in fiscal year 1987. In addition, they will probably receive another 2 or 3 percent through the national laboratories.

Recent budget cuts have seriously affected university and college fusion programs. Over 80 percent of these programs have budgets of less than $1 million, and there are no other sources of Federal funding for fusion research to replace DOE appropriations. Since 1983, two-thirds of the university and college fusion programs have reduced or eliminated their programs. The University Fusion Associates, an informal grouping of individual researchers from universities and col-

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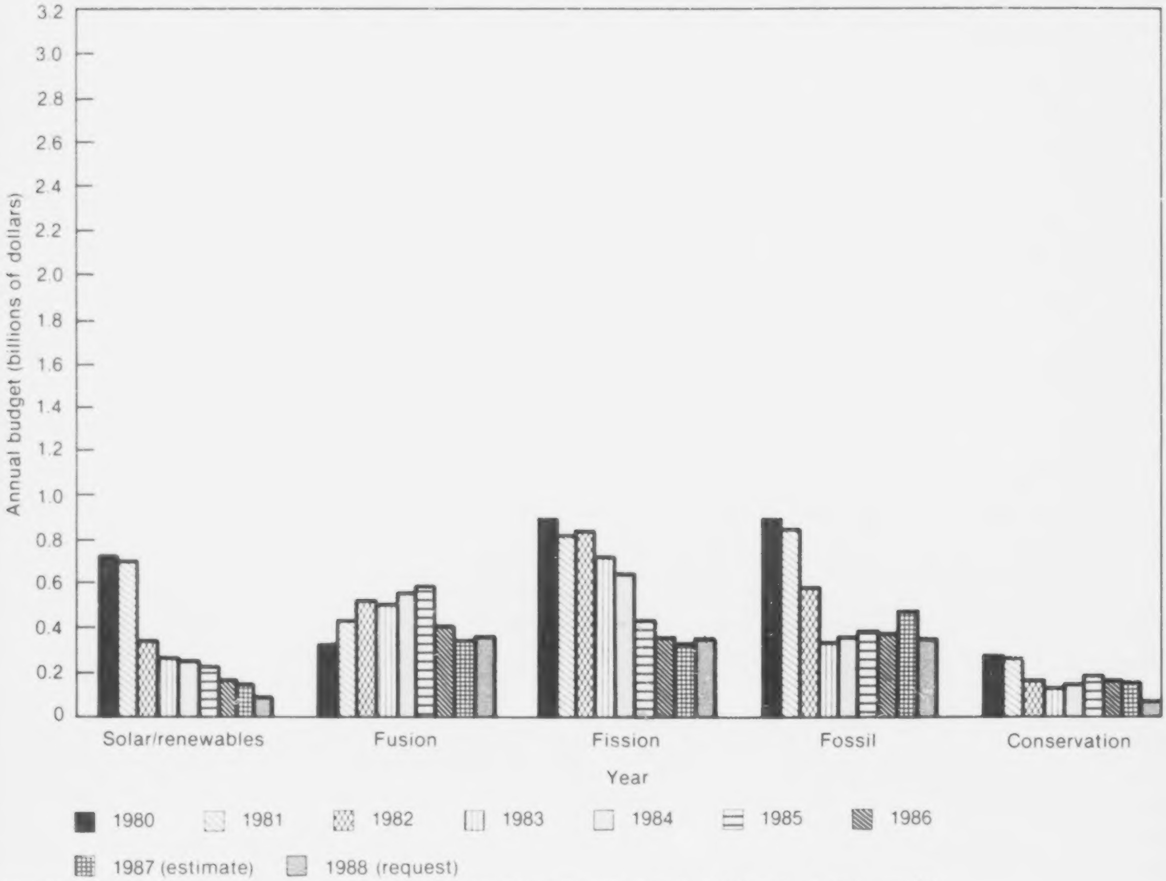
[5] Thomas G. Finn, Department of Energy, Office of Fusion Energy, letter to the Office of Technology Assessment, Mar. 12, 1987. The number of technicians represents only full-time staff associated with experiments; shop people and administrative staff are not included. Figures for scientists and engineers include university professors and post-doctoral appointments; graduate student employees are not included.

[6] John F. Clarke, Director of the DOE Office of Fusion Energy, "Planning for the Future," *Journal of Fusion Energy*, vol. 4, Nos. 2/3, June 1985, p. 202.

Figure 1-6.—Annual Appropriations of DOE Civilian R&D Programs (in current dollars)



SOURCE: Argonne National Laboratory, *Analysis of Trends in Civilian R&D Appropriations for the U.S. Department of Energy*, 1986.

leges, anticipates that as many as half of the institutions represented by its members will eliminate their fusion programs between 1986 and 1989 if the university fusion budgets are not maintained. DOE, however, disputes this claim and projects constant budgets (corrected for inflation) for the university programs.

Private Industry

Private industry can take a variety of different roles in fusion research, depending on its level of interest in the program and the status of fusion development. At the lowest level, industry can serve as an advisor to DOE and the national laboratories. As the research approaches the engineering stage, industry can begin to participate directly by supplying components or contracting with DOE. Ultimately, it is anticipated that industry will sponsor research and development activities.

To date, industry and utility involvement in magnetic fusion R&D has been advisory, with limited cases of direct participation. This is due largely to fusion's long time horizon and the lack of predictable, easily commercializable "spin-off" technologies. Most current industrial participation is facilitated through subcontracts from national laboratories.

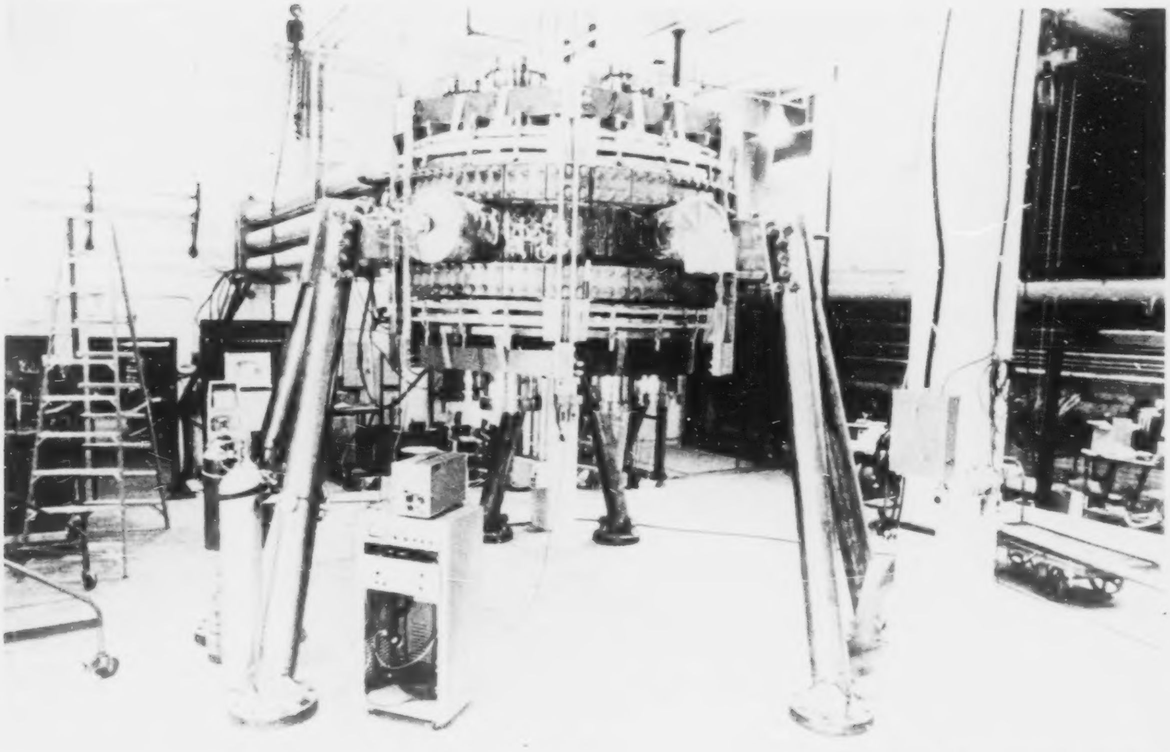


Photo credit: Plasma Fusion Center, MIT

The Alcator C tokamak at the Massachusetts Institute of Technology.

The transition of responsibility for fusion research and development from government to industry is a significant hurdle to be cleared before fusion can be commercialized. Current DOE policy calls for any demonstration fusion reactor to be built and operated by the private sector. Industries and utilities, on the other hand, may be unwilling to risk a major investment in a new and unproven technology.

There is considerable controversy over the appropriate time for the private sector to become more involved in the research program. Some argue that the willingness of industry to invest in fusion technology should not be used as a criterion for determining its appropriate degree of involvement. They maintain that early involvement of industry in fusion research is necessary to ensure that the technology will be attractive to its eventual users and marketable by the private sector. Others counter that, given present and foreseeable future research budgets, there are not enough opportunities for the private sector to develop and maintain a standing capability in fusion. These individuals believe that industry's limited participation in fusion research in the near-term will not preclude its eventual role in demonstration and commercialization.

Chapter 6 of this report describes characteristics of fusion as a near-term research program—its near-term benefits, its financial and personnel needs, and its principal participants.

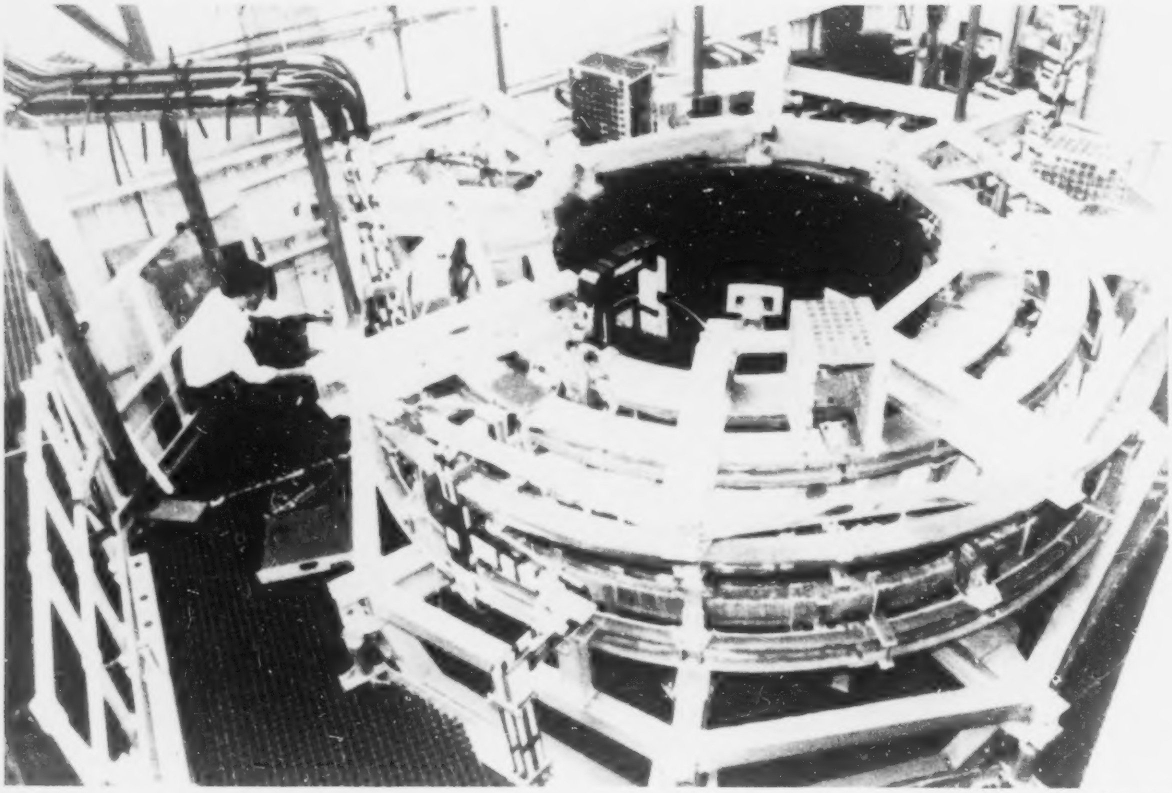


Photo credit: GA Technologies

The Ohmically Heated Toroidal Experiment at GA Technologies, Inc., which is the only major fusion experiment constructed and operated largely with private funds.

FUSION AS AN INTERNATIONAL PROGRAM

The field of magnetic fusion research has a 30-year history of international cooperation. The leaders of the U.S. fusion community continue to support cooperation, as does DOE. In the past, the United States cooperated internationally in a variety of exchanges that have produced useful information without seriously jeopardizing the autonomy of the domestic fusion program. In recent years, in response to budgetary constraints and the technical and scientific benefits of cooperation, DOE has begun cooperating more intensively in fusion, and the major fusion programs have become more interdependent. For the future, DOE proposes undertaking cooperative projects that will require the participating fusion programs to become significantly interdependent: **indeed, DOE now sees more extensive international cooperation as a financial necessity.**

Opportunities for Increased Collaboration

Cooperation among the major world fusion programs can be expected to continue at its current level, at the least, as long as each of the major fusion programs maintains a level of effort sufficient to make it an attractive partner to the others. In the future, it is also possible that a substantially expanded degree of collaboration may take place. Such collaboration may take two forms:

joint construction and operation of major facilities on a scale not yet attempted among the four programs, and substantial additional joint planning among the world programs to minimize redundant research and to maximize the transfer of information and expertise among the programs.

Those who favor increased levels of collaboration believe that there will be important opportunities over the next decade. At the same time that similarities in the status and goals of the major international fusion programs provide a technical basis for expanded cooperation, the comparable levels of achievement ensure that each program can contribute to and benefit from collaboration. Moreover, commercial applications of fusion technology are sufficiently far off that competitive concerns should be minimal. Since the programs may not remain comparable over the long term, these pro-collaboration observers maintain that the timing may not be as advantageous for collaboration in the future as it is now. In particular, they worry that if recent funding trends continue, the U.S. fusion program may fall behind the other programs and might no longer be viewed as a desirable partner.

Benefits and Liabilities of Cooperation

International collaboration introduces a number of potential benefits and liabilities to the participants. Observers will weigh these features differently, arriving at different conclusions about the value of collaboration:

- **Knowledge Sharing.** All forms of cooperation involve sharing knowledge. Researchers can take advantage of one another's experience, greatly aiding their own progress. Some observers, however, are concerned that collaboration could lead to exchange of information that has adverse implications for national security or technological competitiveness.
- **Cost Sharing.** Cooperation can save the partners money by spreading out the costs of experiments among the participants and avoiding duplication of effort. Some additional costs may be added as a result of increased administrative complexity, but barring unusual circumstances each partner should spend less through collaboration than it would to duplicate the research by itself.
- **Risk Sharing.** The financial and programmatic costs of a collaborative project are spread among a number of participants, minimizing the exposure of any one of them in the event of failure. On the other hand, through collaboration, each party opens itself up to the risk that withdrawal of any of the other partners may jeopardize the success of the entire project. A partner may also become dependent on others for the continuation of its own program. Finally, some observers feel that the absence of competition and duplication among experimental facilities may increase the risk of technical failure.
- **Diplomatic and Political Implications.** Collaboration can be diplomatically motivated, because it may improve relations and increase familiarity between the partners. Some analysts welcome this additional aspect of collaboration; others fear that diplomatic motivations may override technical ones, causing a project to be undertaken that might not be judged attractive on its technical merits alone.
- **Domestic Implications.** If the domestic program is neglected in order to support the collaboration, both the ability of the partner to collaborate and the value of collaboration to that partner may be compromised. Even if the domestic program is not damaged, it will be influenced by participation in collaboration. Becoming dependent on collaboration lessens the flexibility of the partners to change research direction and emphasis. On the other hand, collaboration can stabilize domestic efforts; the additional commitment given to a collaborative effort makes it more difficult for domestic contributions to that effort to be cut back.

Obstacles to International Cooperation

The process of organizing and executing large-scale collaboration presents challenges that must be overcome by each of the partners. Among the challenges will be siting the facility, resolving the technology transfer concerns of the parties and making them compatible with an open exchange of research results, resolving technical differences among the parties, and overcoming a variety of administrative obstacles including different institutional frameworks, different budget cycles, different legal systems, and personnel needs.

Negotiating and executing workable agreements for international collaboration will undoubtedly be a difficult and time-consuming process. Legal and institutional frameworks must be devised that address the issues in a manner acceptable to participants in the project.

The International Thermonuclear Experimental Reactor

Currently, most of the effort in international collaboration is focused on a proposal to develop a conceptual design for an international engineering test reactor, called the International Thermonuclear Experimental Reactor (ITER). Estimates indicate that building an engineering test reactor will cost well over $1 billion and possibly several times this amount, which is far more than the U.S. fusion program has spent on any one facility in the past and is too expensive for the United States to undertake alone without substantial increases in fusion funding. Therefore, DOE is involved in discussions with the other worldwide fusion programs to jointly design, construct, and operate ITER.

At this stage, only the conceptual design of ITER is being considered by the potential collaborators; the U.S. Government recently issued a proposal to begin a joint planning activity on a conceptual design for the experiment, along with supporting R&D. It is anticipated that the conceptual design phase of ITER will occur between 1988 and 1990 at a total estimated cost ranging from $150 million to $200 million. The U.S. cost of the undertaking is projected to be between $15 million and $20 million annually over the 3-year program.

Since the U.S. Government proposal addresses only the conceptual design phase of ITER, it makes no commitment to future construction of a collaborative experiment. Therefore, current negotiations will not address the obstacles to international collaboration that would arise if and when the decision were made to jointly construct and operate the device. At the completion of the conceptual design phase, interested parties would be in a position to begin negotiations on whether or not to proceed with construction. The existence of a conceptual design would make it easier to resolve many of the questions that would arise should a subsequent decision be made to build and operate ITER. In particular, it should be possible to analyze concerns about technology transfer specifically and determine their implications for national security or industrial competitiveness.

International cooperation on the scale required for ITER is unprecedented for the United States. Reaching agreement within the U.S. Government to initiate and maintain support for ITER over the lifetime of the project will probably require a Presidential decision. Even that, by itself, is insufficient to guarantee the viability of a project involving all branches of the U.S. Government and extending over several Presidential administrations.

At this time, DOE considers international collaboration on the scale of ITER to be crucial. Given the seriousness of the obstacles, however, it is possible that such collaboration may not occur. **In the event that no major collaboration takes place, either the U.S. fusion program will have to be funded at a higher level or its schedule will have to be slowed down and revised.**

International issues are discussed in chapter 7 of this report.

Chapter 2

Introduction and Overview

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Chapter 2

Introduction and Overview

FUSION POWER

To geologists and physicists at the turn of the century, the term "energy problem" referred not to finding sources of energy for society, but to identifying the one used by the sun. Most physicists believed that the source of the sun's energy was heat released as the sun slowly shrank under its own gravity, a process that would burn out no more than 20 million years after the sun was formed. Geologists, however, argued that geological and fossil evidence showed that the earth—assumed to be no older than the sun—was in fact many times more than 20 million years old.

Although many hypotheses were developed to reconcile the two positions, it was not until 1938 that one explanation received virtually instantaneous and universal acclaim: the sun's "energy problem" was solved when nuclear fusion was identified as its energy source. Through fusion, the sun has been able to shine for nearly 5 billion years using only about half of its original fuel.

Nuclear fusion is the process by which the nuclei—or central cores—of two atoms combine or *fuse* together. The total mass of the final products is slightly less than the total mass of the original nuclei, and the difference—less than 1 percent of the original mass—is released as energy. Nuclear fusion, in a sense, is the opposite of nuclear *fission*, the process utilized in existing nuclear powerplants. In a fission reaction, energy is released when a heavy nuclei splits into smaller pieces whose total mass is slightly less than that of the original nucleus.

Nuclear fusion may be applicable to the energy needs of humans. If the fusion process can be utilized economically, it has the potential to provide society with an essentially unlimited source of electricity. It may also offer significant environmental and safety advantages over other energy technologies, characteristics that are particularly appealing in a world where no energy technology is perfect. Since the 1950s, the potential payoff of fusion energy has motivated a worldwide research effort.

The previous decades of research have shown that fusion energy is extremely difficult to produce. Experiments planned for the next few years should be able to assess fusion's scientific feasibility as an energy source, but several decades of additional research and development, and billions of additional dollars, will be needed to see whether a marketable fusion reactor can be developed. Researchers in the United States, Western Europe, Japan, and the Soviet Union generally agree on the technical tasks yet to be done to evaluate fusion's potential. Policymakers in these nations must now decide if, when, and how to allocate the resources necessary to accomplish these tasks.

The Allure

In the future, fusion power could be an attractive source of energy because it might offer a combination of benefits unmatched by other fuels. Compared to other energy technologies, fusion could be:

- **Unlimited.** A form of hydrogen found naturally in water is a potential fusion fuel, and every gallon of water on earth contains the fusion energy equivalent of 300 gallons of gasoline.
- **Clean.** Using fusion reactions to generate power may be significantly cleaner than either fossil fuels or nuclear fission. Fusion, unlike coal combustion, does not produce carbon dioxide whose accumulation in the atmosphere may affect world climate. Moreover, fusion will not contribute to acid rain or other potential environmental damage associated with fossil fuels. Although fusion reactors themselves will become radioactive, the products of the fusion reaction are not radioactive. With appropriate choice of struc-

tural materials, fusion reactors will produce far less radioactive waste than fission reactors.

- **Safe.** It may be possible to design fusion reactors in which safe operation is assured by physical properties, rather than by active safety systems that might fail due to malfunction, operator error, or natural disaster.

Substantial further scientific and technological development is required to see whether these benefits can be attained.

Establishing Fusion's Feasibility

Two requirements must be met before fusion can be an attractive source of energy. First, fusion's *technological feasibility* must be demonstrated by establishing the scientific and engineering understanding necessary to build an operating fusion reactor. Second, fusion's *commercial feasibility* must be demonstrated.

Technological feasibility is usually considered in two stages: *scientific feasibility* and *engineering feasibility*. Scientific feasibility requires generating a fusion reaction that produces at least as much energy as must be input into the plasma to maintain the reaction. This milestone, called *breakeven*, has not yet been reached, but it is expected that breakeven will be accomplished in existing machines by 1990.

Simply breaking even, however, does not show that fusion can serve as a useful source of energy. In addition, a fusion reaction must be created that has *high energy gain*, producing an energy output many times higher than its energy input. No existing experiment has the capability to produce such a reaction, a task that is more significant and more difficult to achieve than breakeven. However, the Department of Energy (DOE) has requested funds in its fiscal year 1988 budget to begin construction of an experiment to generate a reaction with such high-gain that it should become self-sustaining, or ignited. At *ignition*, reactions will generate enough power to sustain the fusion process even after external heating power has been shut off.

After high gain or ignition has shown fusion's scientific feasibility, its engineering feasibility must be demonstrated. This accomplishment will entail developing future reactor systems, subsystems, and components that can function reliably under reactor operating conditions. Demonstrating engineering feasibility will require an extensive amount of research and development, and it will be a technical achievement at least as impressive as the scientific accomplishment of harnessing controlled fusion reactions.

Although scientific feasibility and engineering feasibility involve different issues, fusion science and fusion engineering are interdependent: advancing scientific understanding of the fusion process requires improved technological capabilities in experimental facilities, just as solving the engineering problems posed by fusion reactor design requires additional basic understanding in a number of areas. Demonstrating both the scientific and engineering feasibility of fusion power requires advances to be made in basic scientific understanding as well as in technological capability.

The goal of fusion research is to establish fusion's technological feasibility in a manner that makes commercial feasibility likely. If and when it becomes clear that generating electricity in a fusion reactor is possible, such a reactor must prove socially and environmentally acceptable and economically attractive compared to its alternatives. Although dependent on the technical results of fusion research, fusion's commercial feasibility also involves factors unrelated to the technology itself, such as the status of other energy technologies and the regulatory and licensing structure. Commercial feasibility ultimately will be determined by individuals and institutions that are not involved directly in fusion research.

The Fusion Reaction

Only light elements can release energy through fusion. While many different fusion reactions take place in the stars, the one that can be used most easily to generate power on earth involves *hydrogen (H)*, the lightest element. Three forms, or *isotopes*, of hydrogen exist: *protium*, which is usually referred to simply as hydrogen, *deuterium (D)*, and *tritium (T)*. The nuclei of these isotopes consist of a single proton and zero, one, or two neutrons, respectively. Over 99.98 percent of all hydrogen found in nature is the protium isotope. Less than 0.02 percent (one part in 6,700) is composed of deuterium. Tritium is radioactive, with a half-life of 12¼ years;[1] it is practically nonexistent in nature, but it can be manufactured.[2]

The easiest fusion reaction to initiate combines deuterium and tritium to form helium and a free neutron, as shown in figure 2-1; a fission reaction is also shown for comparison. The fusion reaction shown—called a D-T reaction—liberates 17.6 million electron volts[3] of energy. By way of comparison, burning a single atom of carbon (the combustible material in coal) releases only about 4 electron volts. Therefore, a single D-T fusion reaction is over 4 million times more energetic.

Four-fifths of the energy released in a D-T fusion reaction is carried off by the neutron as kinetic energy. In a fusion reactor, it is anticipated that neutrons would be captured in the material surrounding the reaction chamber, where their kinetic energy would be converted into heat. One-fifth of the reaction energy, carried off by the helium nucleus, would remain inside the reaction chamber, heating up the fuel and making additional reactions possible.

The primary application of fusion will probably be for electric power generation, using heat from the fusion reaction to boil water to drive a steam turbine that generates electricity. Advanced systems for converting fusion energy more directly into electricity may also be possible. Other applications of fusion might use the neutrons themselves for various purposes, rather than just extracting their energy. It is also possible that, as fusion development progresses, additional uses of the technology might be found. The potential characteristics of fusion reactors used to produce electricity are discussed in chapter 5; other possible applications of fusion are discussed in appendix A.

The D-T reaction is not the only one that can generate fusion energy. One deuterium nucleus can fuse with another in a D-D reaction. It is also possible to use other light elements besides hydrogen as fuel. However, it is much harder to initiate fusion reactions with fuels other than deuterium and tritium, and many of these alternate fuels produce less power for a given amount of fuel than the D-T reaction does. Reactors using alternate fuels would be more difficult to design and build than D-T reactors producing the same amount of energy. On the other hand, these alternate reactions may not require tritium production and/or may not generate as many neutrons as the D-T reaction. Both tritium production and neutron generation increase the amount of radioactive material contained in a reactor, a situation that complicates the reactor's design and can raise environmental and safety issues.

Requirements for Fusion Reactions

Fusion reactions can only occur when the requirements of *temperature*, *confinement time*, and *density* are simultaneously met. The minimum temperatures, confinement times, and densities needed to produce fusion power have been known for decades. Achieving these conditions in experiments, however, has proven extremely difficult.

Temperature

Because the nuclei that must fuse have the same electrical charge, they must be heated to extremely high temperatures to overcome their natural repulsion. Temperatures on the order of 100 million degrees Celsius (C) are required. No matter exists in solid form at these temperatures; individual atoms are broken down—ionized—into their constituent electrons and nuclei. With their outside electrons missing, the nuclei have a positive electric charge and are called *ions*.

Matter in this state is called *plasma* (figure 2-2). Plasma is considered a fourth state of matter

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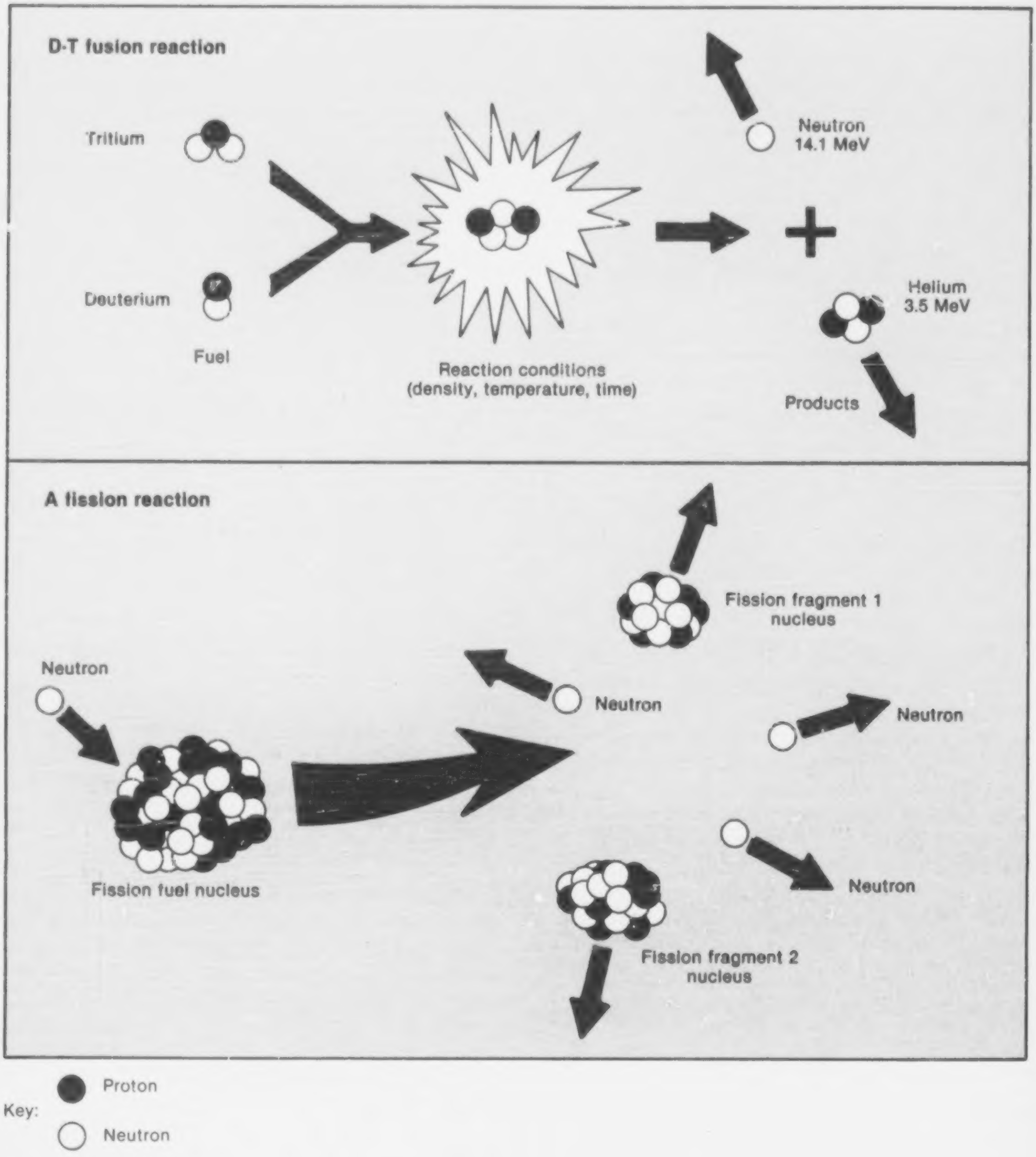
[1] Radioactive materials decay over time as the nuclei of radioactive atoms emit radiation and transform into other nuclei. The decay rate is measured by the substance's *half-life*, which is the time required for half of the nuclei to be transformed.

[2] Trace amounts of tritium are continually produced by cosmic rays in the upper atmosphere. Most of the tritium now in the environment, however, was produced by atmospheric nuclear weapons tests in the 1950s.

[3] One electron volt (eV) is the energy that a single electron can pick up from a 1-volt battery. It is equal to 1.6×10^{-19} joules, 1.52×10^{-22} Btu, or 4.45×10^{-26} kilowatt-hours. One thousand electron volts is called a kiloelectron volt, or keV.

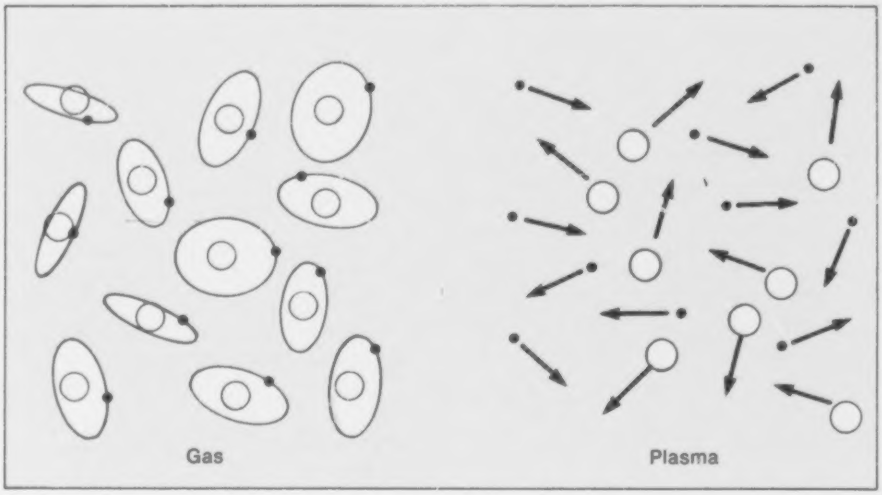
Figure 2-1.—The D-T Fusion Reaction and a Fission Reaction


D-T fusion reaction
Tritium
Deuterium
Fuel
Reaction conditions (density, temperature, time)
Neutron 14.1 MeV
Helium 3.5 MeV
Products
A fission reaction
Neutron
Fission fuel nucleus
Fission fragment 1 nucleus
Neutron
Neutron
Neutron
Fission fragment 2 nucleus
Key:
Proton
Neutron

MeV: million electron volts

SOURCE: Adapted from Princeton Plasma Physics Laboratory, Information Bulletin NT-1: Fusion Power, 1984, p. 2 (fusion); Office of Technology Assessment (fission), 1987.

Figure 2-2.—Gas and Plasma



SOURCE: Princeton Plasma Physics Laboratory, Information Bulletin NT-1: Fusion Power, 1984, p. 3.

because it has properties unlike solids, liquids, or gases. Fusion research, critically dependent on understanding plasmas, has led to the development of a new field of science called *plasma physics*.

The temperature of a plasma is a measure of the average energy of the plasma particles and is usually expressed in units of *electron volts*. A plasma temperature of 1 electron volt, which is about 11,600° C, corresponds roughly to each particle in the plasma having an average energy of 1 electron volt. In a plasma, the ions and the electrons can have different temperatures; ion temperature is most important and must exceed about 10,000 electron volts for enough of the ions to overcome their mutual repulsion to produce appreciable amounts of fusion power.

Confinement Time

The goal of fusion research is not only to create a hot plasma but also to keep it hot long enough to produce fusion power. It is not sufficient simply to heat the fuel, because any substance that is hotter than its surroundings will cool off. The rate at which the substance cools depends on its physical characteristics, its surroundings, and the temperature difference between the two. The ability of a plasma to stay hot is represented by its *confinement time*, which is a measure of the time it would take to cool down to a certain fraction of its initial temperature if no additional heat were added.

With an insufficient confinement time, it is impossible to reach breakeven or ignition. Even if the plasma is heated hot enough for fusion reactions to start, heat would be lost faster than it would be generated in those reactions, and the reactions would not produce any net power. Confinement times on the order of one second are generally considered necessary for an ignited plasma.

Density

The exact confinement time requirement depends on plasma *density*. The fusion reaction rate, and therefore the amount of fusion power produced by the plasma, goes down rapidly as density drops. A plasma that is not dense enough will not be able to generate power even if it is very hot and retains its heat very well. The density required to reach breakeven or ignition increases as confinement time decreases. The product of density and confinement time (called the *Lawson parameter*) must exceed a minimum threshold in order for a fusion plasma to ignite.[4]

Confining Fusion Plasmas

A fusion plasma cannot be contained in an ordinary vessel no matter how hot the vessel is heated, because the plasma will be instantly cooled far below the minimum temperature required for fusion whenever it comes into contact with the vessel walls. There are three primary ways to hold a plasma that avoid this obstacle. Only one of these—*magnetic confinement*—is discussed to any appreciable extent in this report.

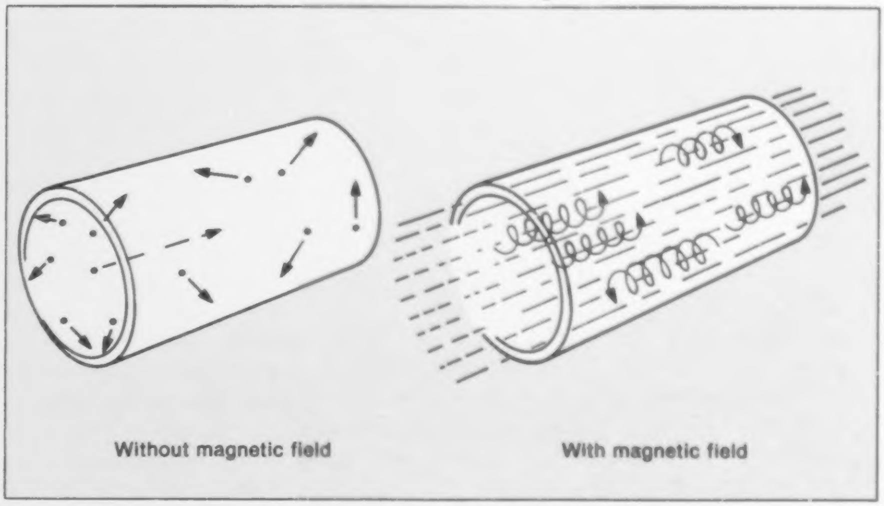
Magnetic Confinement

Magnetic confinement relies on the fact that because individual particles in a plasma are electrically charged, their motion is strongly affected by magnetic fields. A charged particle moving in a magnetic field will be bent at right angles to both the direction of the field and its direction of motion, with the result that the energetic particles making up a fusion plasma will trace spiral orbits around magnetic field lines (figure 2-3). Magnetically confined plasmas will tend to flow along field lines but not across them, and a suitable configuration of magnetic fields can therefore confine a plasma. Many different kinds of magnetic-confinement configurations are under investigation, as described in chapter 4. **In this report, the word fusion refers to magnetic confinement fusion unless specifically noted otherwise.**

Gravitational Confinement

A sufficiently large plasma can produce fusion power while holding itself together with its own gravitational field. This process, called *gravitational confinement*, permits fusion to take place in the sun and other stars. It is impossible, however, to utilize gravitational confinement for fusion processes on earth. Even the planet Jupiter, which is over 300 times more massive than earth, does not have sufficient mass to produce gravitationally confined fusion.

Figure 2-3.—The Motion of Charged Particles



SOURCE: Princeton Plasma Physics Laboratory, Information Bulletin NT-1: Fusion Power, 1984, p. 3.

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[4] The minimum threshold for ignition, as defined by the Lawson parameter, is 3×10^{14} second-particles per cubic centimeter. This means that a plasma with a density of 3×10^{14} particles per cubic centimeter must be confined for one second in order to ignite. As mentioned above, if the density were increased to 3×10^{15} particles per cubic centimeter, then the confinement time requirement would decrease to one-tenth (0.1) of a second.

Inertial Confinement

In a hydrogen bomb, fusion fuel is heated and compressed to such high densities that it need be confined only for a very short time in order to generate fusion power. The fuel's own *inertia* keeps it confined long enough for fusion reactions to occur. A research effort is now underway to study this *inertial confinement* process in a controlled manner on a laboratory scale. This program has near-term military applications, due to its close connection with weapons physics, and may have longer term energy applications as well. The energy applications of inertial confinement fusion are generally considered less developed than those of the magnetic confinement process. Because of the direct links between this approach and hydrogen bomb design, much of the research in inertial confinement fusion is classified. The inertial confinement approach is discussed in appendix B.

THE PURPOSE OF THIS STUDY

Increasing budgetary pressures, along with a decreasing sense of urgency regarding energy supply, have sharpened the competition for funding between one research program and another and, perhaps more significantly, between energy research programs and other components of the Federal budget. At the same time, issues such as the implications of increased fossil fuel usage on the global climate and the long-term acceptability of nuclear power have raised serious concerns about future energy supply.

In balancing the long-term potential of fusion energy against shorter term, more immediate pressures, the congressional committees with jurisdiction over DOE's magnetic fusion program requested this study. In 1986, the House Committee on Science and Technology requested that OTA review the magnetic fusion energy program, citing that ". . . a number of factors have served to decrease the sense of urgency with which the DOE management and many members of the Congress view the development of fusion power." Shortly afterward, the Senate Committee on Energy and Natural Resources endorsed this request. These committees are faced with setting policy for the fusion program, and they were interested in an independent analysis of the fusion program as input to their budget authorization deliberations.

In response, OTA undertook this assessment of the magnetic fusion research and development program in March 1986. The assessment examines the technical and scientific achievements and objectives of the fusion program. It also analyzes the program from three different, but related, perspectives:

1. It considers the issues related to fusion's role as an energy research and development program, in particular those related to developing an attractive energy supply technology.
2. It analyzes the near-term, non-energy benefits of the fusion program and the financial and personnel resources necessary to support the program.
3. It examines the increasing role of international collaboration in magnetic fusion research.

OTA's assessment was carried out with the assistance of a large number of experts reflecting different perspectives on the fusion program —fusion scientists and engineers, nuclear engineers, environmental scientists, international relations experts, industry and utility executives, consumer groups, economists, financial planners, and energy policy analysts. As with all OTA studies, an advisory panel representing these interests and fields of expertise met periodically throughout the course of the assessment to review and critique interim products and proposals, to discuss fundamental issues affecting the analyses, and to review drafts of the report. Contractors and consultants also provided material in support of the assessment.[5]

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[5] Advisory panel members, workshop participants, contractors, and other contributors to this assessment are listed in the front of this report.

Finally, OTA convened three workshops to clarify important issues considered in the assessment and to review and expand upon contractors' analysis. The first workshop dealt with general issues involved in fusion research. It focused on the nature of the fusion research program, the implications of current funding cuts on the program, and the main issues involved in decisions about future courses of action.

The second workshop addressed issues in international collaboration in fusion research. Three contractor reports, detailing the characteristics of the major non-U.S. fusion programs and their views of collaboration, were reviewed at the workshop. The principal issues addressed were the motivations and goals of foreign fusion programs, national security and competitiveness risks of technology transfer through collaboration, and other potential obstacles to collaboration.

The final workshop addressed fusion's energy context. Projections of electricity demand in the 21st century and their relevance to fusion were presented by OTA consultants and reviewed. In addition, the uncertainties inherent in forecasting supply and demand over times relevant to fusion were discussed. Alternative energy supply technologies that might compete with fusion were addressed, as were the implications of potential difficulties such as global climate change and nuclear fission safety or environmental issues.

The material in this report is based on OTA staff research, site visits, workshop discussions, advisory panel recommendations, and contractor and consultant reports. The report is organized as follows:

- Chapter 3 provides a brief history of the U.S. fusion program, which, since its inception in the 1950s, has been almost entirely funded by the U.S. Government.
- Chapter 4 explains the technical underpinnings of fusion research and sets out the requirements for demonstrating fusion's technological feasibility. Fusion research is one of the Federal Government's most futuristic and technically complex undertakings. Physical theory and experimentation must advance the present state of the art if the goal is to be reached; forefront technology must be developed not only in the long-run, to harness fusion, but in the short-run to construct each successive experiment.
- Chapter 5 addresses the long-range energy applications of fusion research. The anticipated characteristics of future fusion reactors are discussed, including projected plant economic, safety, and environmental features. Issues involved in commercializing the technology are also examined. In addition, factors that will be important in determining whether and when fusion will penetrate energy markets as a source of electricity are discussed.
- Chapter 6 discusses the character of current fusion research and analyzes the value of the fusion program in terms of its near-term, non-energy benefits. Data on program participants, funding levels, and personnel levels are summarized.
- Chapter 7 examines the extremely important role that international cooperation in fusion research has had in the past and may have in the future. Motivations for and obstacles to future large-scale collaboration are assessed, as well as possible models for such collaboration.
- Finally, chapter 8 summarizes the critical issues facing the fusion program and presents a series of policy paths for Congress to consider as it makes decisions on funding fusion research. The implications of pursuing the different paths are discussed.

Chapter 3
History of Fusion Research

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Chapter 3

History of Fusion Research

RESEARCH BEGINNINGS[1]

Fusion research draws on two independent branches of physics—nuclear physics and plasma physics. Studying the fusion reaction itself is the domain of *nuclear physics*. Studying the behavior of matter under conditions necessary for fusion reactions to take place is the focus of *plasma physics*.

Nuclear Physics

Early in this century, the search for the causes of radioactivity revealed that vast amounts of energy were stored in an atom's nucleus. As early as 1920, this energy was hypothesized to be the heat source that powered the sun and other stars. With the discovery of the neutron in 1932 these nuclear processes began to be understood, and by the time efforts to control fusion reactions in the laboratory began in the 1950s, the nuclear physics underlying laboratory fusion reactions were well known. "Then, as now," noted a recent National Academy of Sciences panel reviewing physics research, "the obstacles to achieving controlled fusion lay not in our ignorance of nuclear physics, but of plasma physics."[2]

Plasma Physics

Plasma physics, according to the same National Academy review panel, is "the only major branch of physics to come largely into being in the past generation."[3] Its development drew upon a number of previously distinct and independent disciplines, pulling them together into a unified methodology for the study of the plasma state.

Explaining plasmas could not begin until the discovery of the electron in 1895 and the development of the atomic theory of matter. Between 1930 and 1950, the foundations of plasma physics were laid, largely as a byproduct of investigations on topics such as the earth's outer atmosphere, the sun, and various astrophysical phenomena. The advent of space exploration and controlled fusion research—the two major experimental arenas for modern plasma physics—firmly established the field.

Early Fusion Research

The first probe into harnessing fusion power took place during the Manhattan Project, the effort during World War II dedicated to developing an atomic bomb. Some physicists working on the Manhattan Project in Los Alamos, New Mexico, began to consider whether the fusion process could be utilized in nuclear weapons. Such investigations were not a high priority during the war, however, because the national effort was focused on developing weapons that utilized the more immediately promising fission process.

In 1949, largely in response to the first Soviet nuclear detonation, senior U.S. scientists and policymakers conducted an extensive, classified (secret) debate about whether hydrogen bombs—weapons that use the fusion process instead of the fission process—could and should be developed. In 1950, the debate ended when President Truman approved a crash program to build such a weapon. The United States detonated its first H-bomb in 1952.[4]

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[1] Most of the historical material in this chapter is based on *Fusion: Science, Politics, and the Invention of a New Energy Source* (Cambridge, MA: MIT Press, 1982), a comprehensive and extensively documented history of the U.S. fusion program written by Joan Lisa Bromberg under contract with the U.S. Department of Energy. The book is restricted almost entirely to magnetic confinement fusion and covers a period ending in 1978. While Bromberg was given access to unclassified and declassified DOE and national laboratory records, the book does not represent the official position of DOE.

A more popularized history of the fusion program, covering inertial fusion as well as magnetic fusion and extending until 1983, is found in T.A. Heppenheimer, *The Man-Made Sun: The Quest for Fusion Power* (Boston, MA: Little, Brown & Co., 1984).

[2] National Research Council, Panel on the Physics of Plasmas and Fluids, Physics Survey Committee, *Physics Through the 1990s: Plasmas and Fluids* (Washington, DC: National Academy Press, 1986), p. 4.

[3] Ibid., p. 6.

In the beginning, most research in thermonuclear fusion was weapons-related and classified. This research fell under the constraints of the Atomic Energy Act of 1954, which mandated that data concerning the "design, manufacture, or utilization of atomic weapons," as well as "the production of special nuclear material" and the "use of special nuclear material in the production of energy," remain classified indefinitely unless specific action was taken to declassify it.[5]

Over the years, some of the emphasis in fusion research shifted from weapons to reactors. Fusion reactors were sought not only to produce "special nuclear materials"—tritium and plutonium—needed for nuclear weapons, but also to produce electricity. At the time, both energy production and materials production fell under the restrictions of the Atomic Energy Act that mandated continued classification.

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[4] Herbert York, "The Debate Over the Hydrogen Bomb," *Scientific American*, October 1975. There are many names for bombs that use the fusion process: hydrogen bombs, H-bombs, and thermonuclear or hydrogen weapons. Such weapons can have many times the explosive power of fission weapons.

[5] "Special nuclear material," as defined in the Atomic Energy Act of 1954, is material capable of undergoing nuclear explosions.

THE U.S. FUSION PROGRAM THROUGH THE DECADES

The nature of the U.S. fusion research program through each decade from its conception to the present is summarized below. The funding profile for U.S. fusion research, both in constant and current dollars, is shown in figures 3-1 and 3-2. Data for these figures is provided in appendix C; for more information on funding for magnetic fusion research, see chapter 6.

The U.S. Atomic Energy Commission (AEC) was responsible for magnetic fusion research from 1951, when the program was formally undertaken, until 1974, when the AEC was disbanded and replaced by the Energy Research and Development Administration (ERDA). In 1977, ERDA in turn was disbanded and its responsibilities transferred to the new Department of Energy (DOE). Since 1977, DOE has managed the magnetic fusion research program.

The 1950s: Era of Optimism and Disillusionment

Project Sherwood

From 1951 until 1958, fusion research was classified; during these years, the program was conducted under the code name "Project Sherwood." At the outset of Project Sherwood, both field scientists and program managers at the AEC believed that fusion could yield an important technology to supply future electricity needs. In pursuing fusion, scientists and AEC commissioners sought to maintain U.S. scientific supremacy; there could be significant political and economic advantage should fusion lead to a commercially competitive new energy technology. Fusion research would also support the U.S. weapons program. The potential use of fusion reactors for generating weapons materials, as well as the possibility of other military applications, was important to the AEC; thus, during the early 1950s, fusion research grew along with military atomic research.

Project Sherwood began optimistically in 1951. At that time, it was estimated that spending about $1 million over a period of 3 to 4 years would be sufficient to learn whether a high-temperature plasma could be confined by a magnetic field. About that amount was budgeted for fusion research from 1951 to 1953. However, the problem proved harder than originally anticipated, and in 1953 the fusion research program expanded. The personnel level increased from 8 in 1952 to 110 in 1955 and rose to over 200 people in 1956. Annual budgets increased from under $1 million to $7 million over the same period.[6]

The United States established several fusion research centers. Federally funded efforts were con-

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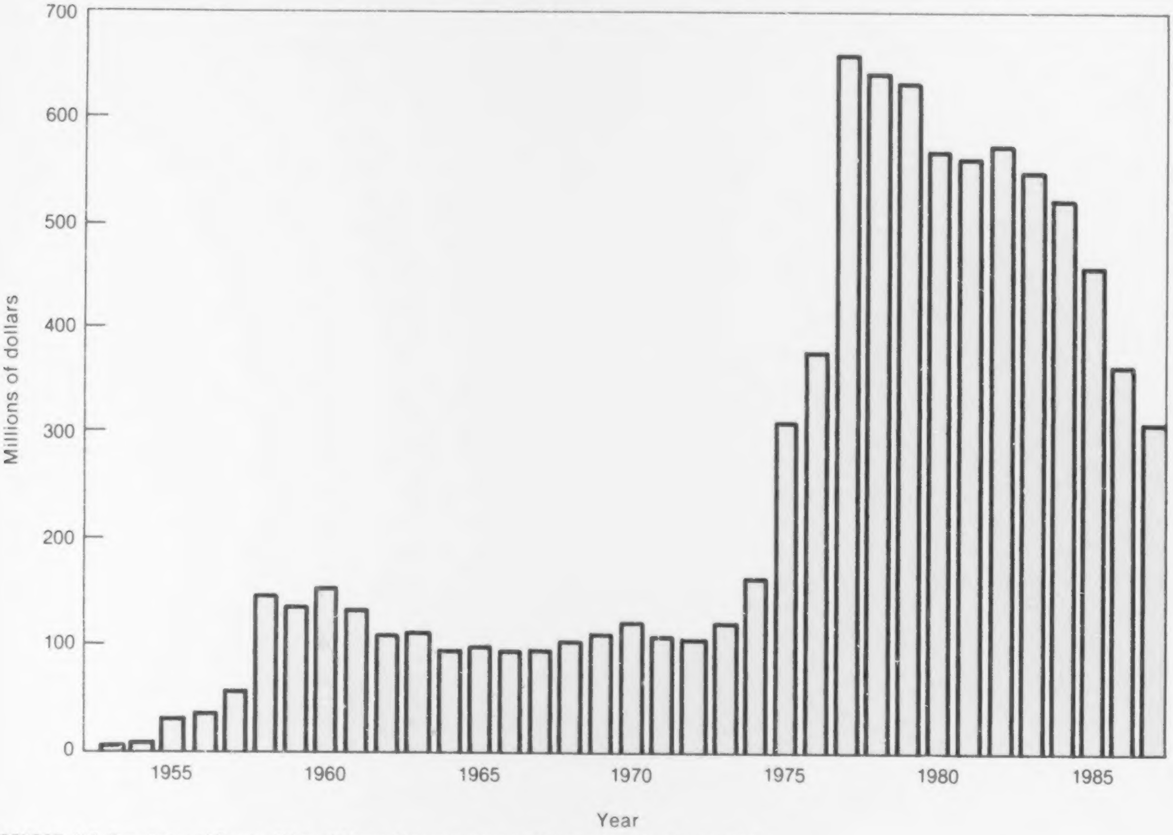
[6] Bromberg, *Fusion*, op. cit., p. 30.

Figure 3-1.—Historical Magnetic Fusion R&D Funding, 1951-87 (in 1986 dollars)



SOURCE: U.S. Department of Energy, Office of Energy Research, letter to OTA project staff, Aug. 15, 1986

ducted at Oak Ridge National Laboratory in Tennessee, Los Alamos Scientific Laboratory in New Mexico, Lawrence Livermore Laboratory in California, and a number of universities, including a major plasma physics laboratory at Princeton University in New Jersey established primarily to conduct fusion research. Private or corporate-sponsored research began in 1956 at the General Electric Co. (GE) in New York and at the newly created General Atomic Corp. in California. Several other companies dedicated a few staff members to monitor the field.

Many different confinement schemes were explored during the early 1950s. Although proponents of the various schemes were careful to note that practical applications lay at least 10 or 20 years in the future, the devices under study were thought to be capable of leading, in a straightforward process of extrapolation, to a commercial reactor. One report concluded in 1958:

> With ingenuity, hard work, and a sprinkling of good luck, it even seems reasonable to hope that a full-scale power-producing thermonuclear device may be built within the next decade or two.[7]

In reality, very little was known about the behavior of matter under the conditions being studied, much less under reactor-like conditions. Experiments were trial-and-error operations, and each one charted new ground. Results were often

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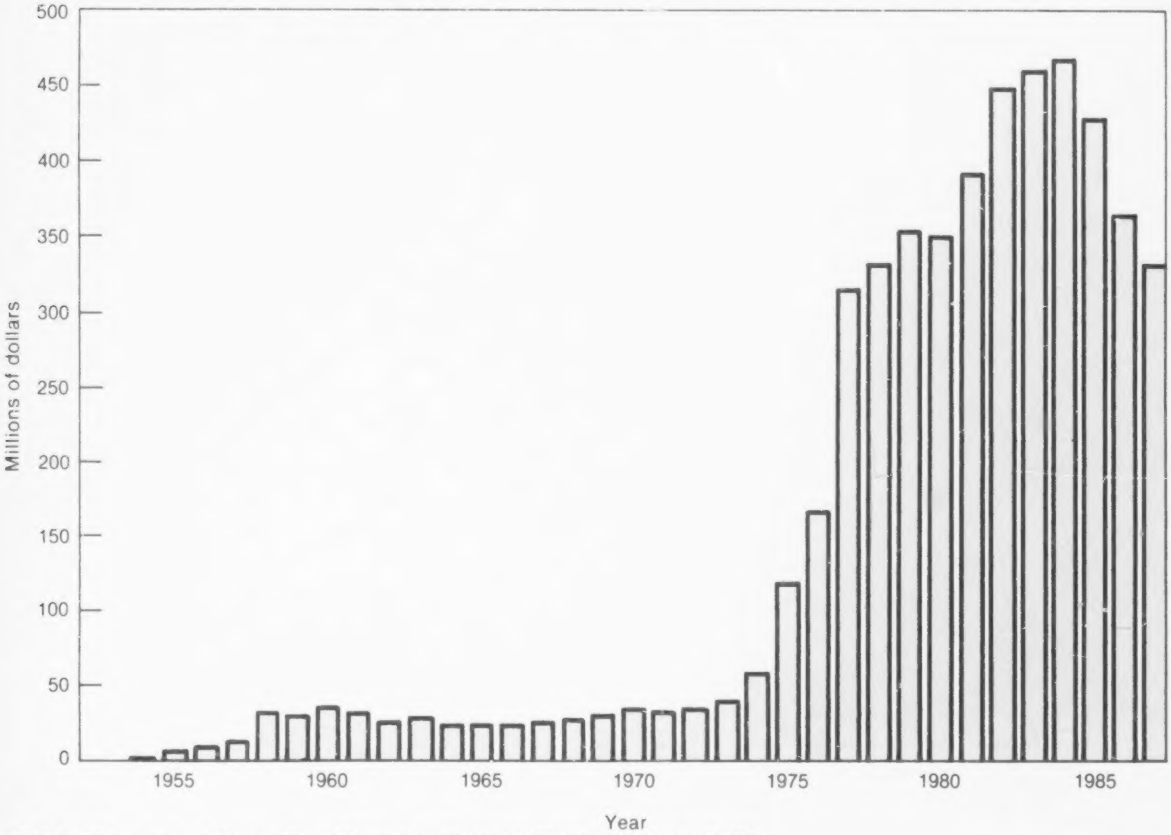
[7] Amasa S. Bishop, *Project Sherwood: The U.S. Program in Controlled Fusion* (Reading, MA: Addison-Wesley Publishing Co., Inc., 1958), p. 170. Bishop managed the AEC fusion program from 1953 to 1956 and again from 1965 to 1970.

Figure 3-2.—Historical Magnetic Fusion R&D Funding, 1951-87 (in current dollars)



SOURCE: U.S. Department of Energy, Office of Energy Research, letter to OTA project staff, Aug. 15, 1986.

ambiguous or misinterpreted, and the theoretical underpinnings of the research were not well established. All devices investigated showed evidence of "*instabilities,*" or disturbances that grew to the point where the plasma escaped confinement faster than expected. The devices studied in the 1950s could not attain Lawson parameters higher than about 10^{10} second-particles per cubic centimeter, a factor of about 10,000 less than the minimum required to make net fusion power.[8] Temperatures attained were about 100 electron volts, in comparison to the minimum requirement of 10,000 electron volts.[9]

Declassification

By the mid to late 1950s, the advantages of declassifying Project Sherwood were recognized, both within the AEC and among scientists in the field. Some U.S. scientists had sought to delay declassification of fusion research because they were optimistic about harnessing controlled fusion reactions in the near future, and they rea-

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[8] The Lawson parameter is the product of density and confinement time (see ch. 2, note 4). The units in which the Lawson parameter is expressed represent a density (particles per cubic centimeter) multiplied by a time (seconds), and have no immediate physical significance. A product of 3×10^{14} second-particles per cubic centimeter is considered the minimum for ignition in a D-T reaction. (See discussion of "energy gain" in ch. 4, pp. 67-68.)

[9] An electron volt is a unit of energy. It is also used as a measure of temperature, representing that temperature at which the average energy of plasma particles is roughly 1 electron volt. (See ch. 2, note 3.)

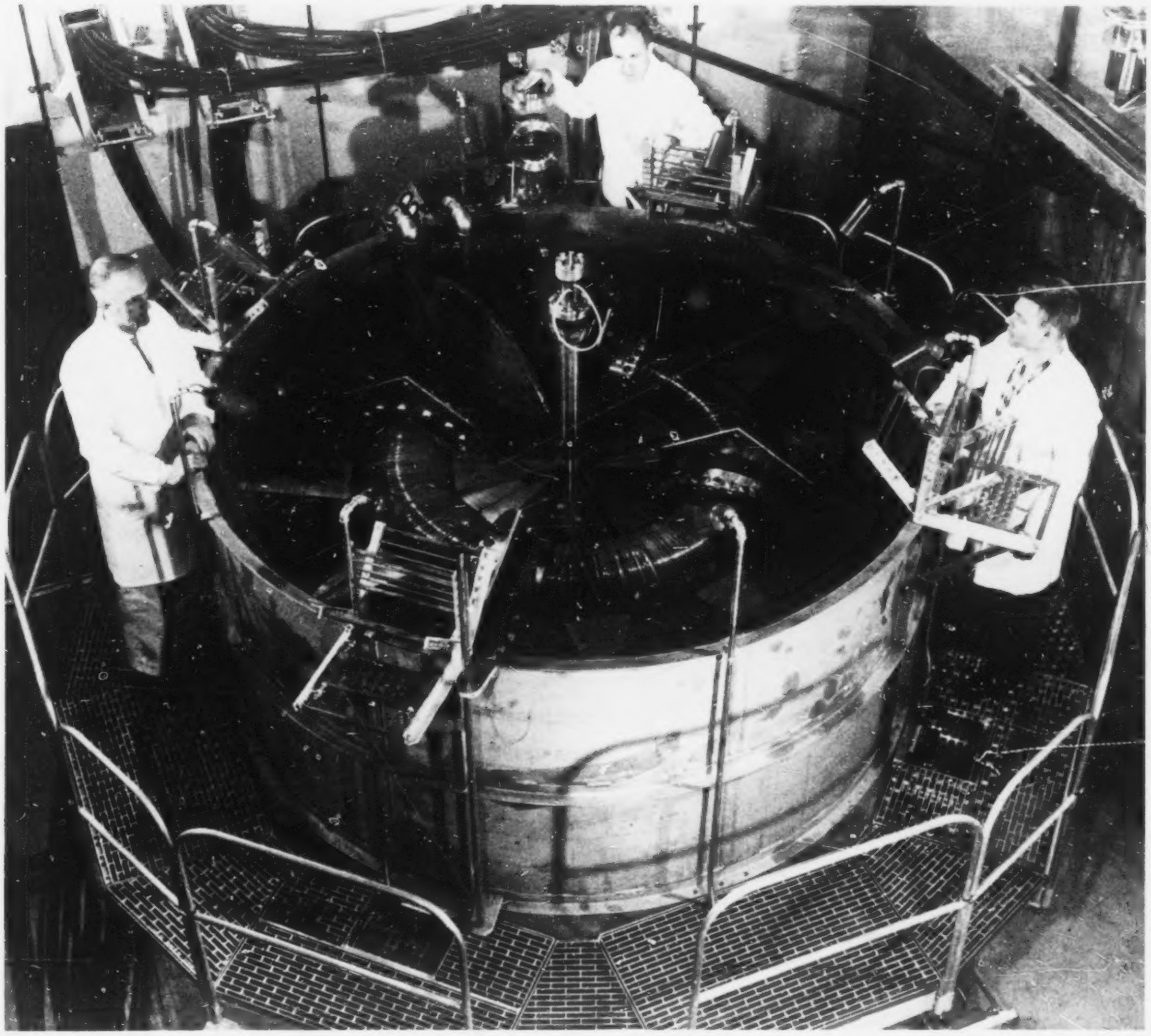

Photo credit: Los Alamos National Laboratory

Perhapsatron, built and operated in the 1950s at Los Alamos Scientific Laboratory.

soned that declassification would have more impact if it came with an announcement to the world of the successful production of thermonuclear reactions.[10] Most researchers, however, recognized that attaining fusion conditions in the laboratory was going to be much harder than originally anticipated. These scientists, and the AEC commissioners, came to believe that developing fusion power would be easier in an atmosphere of open communication and scientific interchange made possible by declassification.

At the same time, the security considerations that had justified classification became less important. New supplies of uranium for weapons applications were discovered. Moreover, fission technology, which had been used successfully to generate plutonium and tritium for nuclear weapons, was being declassified. It did not make sense to classify fusion research, whose application in producing weapons material was still hypothetical, after fission technology that was actually being used for that purpose was declassified.[11]

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[10] Bromberg, *Fusion*, op. cit., pp. 69 and 284, note 11.

U.S. magnetic fusion research was declassified in 1958 at the Second Geneva Conference on the Peaceful Uses of Atomic Energy. Following declassification, it was apparent that the American, British, and Soviet programs were at more or less the same level and were pursuing similar approaches toward confining plasmas. Declassification opened the door to widespread international cooperation in fusion.

The 1960s: A Plateau

Fusion research in the United States proceeded at a steady pace throughout the 1960s. The theoretical framework advanced, but discrepancies between theoretical predictions and experimental results were common. By the mid-1960s, Congress became impatient. In the late 1950s, members of Congress had believed that the Federal program would be at the reactor prototype level in 5 or 6 years. Since that time, fusion researchers realized that they had seriously underestimated the complexity of the problem. Therefore, the researchers concentrated on studying plasma behavior rather than on building reactor prototypes. Congress, however, worried that the researchers were building an array of different experiments that did not appear to be leading to an attractive reactor.[12] Thus, in 1963, the House Appropriations Committee recommended a 16 percent cut in the program's operating budget. Much of the cut was restored, but the program ended up with a budget of 7 percent less than requested.

Enthusiasm for the fusion program cooled outside of Congress as well. While remaining supportive of fusion, AEC commissioners were more interested in expanding the fission breeder reactor program.[13] GE reviewed its corporate involvement in fusion in 1965 and concluded that "the likelihood of an economically successful fusion electricity station being developed in the foreseeable future is small."[14] GE proposed that the AEC finance its research through a joint effort, but the AEC refused and GE phased out its fusion program. While GE was reconsidering its fusion program, the consortium of Texas utilities that funded fusion research at General Atomic in California withdrew its support.[15] The AEC responded to this decision by funding much of General Atomic's fusion research itself in order to preserve the expertise assembled there. In effect, this response created an additional national laboratory.

In 1965, a prestigious outside review committee evaluated the fusion program. The committee found that the magnetic fusion program had made significant progress, that the United States needed to support research in order to develop the technology, and that the program produced "spin-off" technologies that could benefit the economy. Moreover, the committee stated that the United States would suffer a great loss of international stature if another country demonstrated the feasibility of fusion first. The committee recommended that the fusion budget increase by 15 percent annually and that a new generation of experiments be funded to replace obsolete ones.[16] After considerable deliberation within the AEC and the Bureau of the Budget, an increase in funding was recommended, though not of the magnitude suggested by the committee.

The Tokamak

By 1968, the highest temperatures that had been achieved in a magnetic confinement fusion device were only about 100 electron volts—not appreciably higher than they were in the 1950s. The quality of confinement, as measured by the Lawson parameter, had increased by an order of magnitude (factor of 10) to about 10^{11} second-particles per cubic centimeter. In 1968, however, Soviet scientists announced that they had exceeded the previous best values of each of these parameters by an additional order of magnitude.

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[11] Ibid., pp. 69, 72-73.

[12] Ibid., pp. 118-119.

[13] Ibid., p. 136.

[14] Ibid., p. 137.

[15] This consortium has continued to fund a modest level of fusion research at the University of Texas.

[16] Bromberg, *Fusion*, op. cit., pp. 138-139.

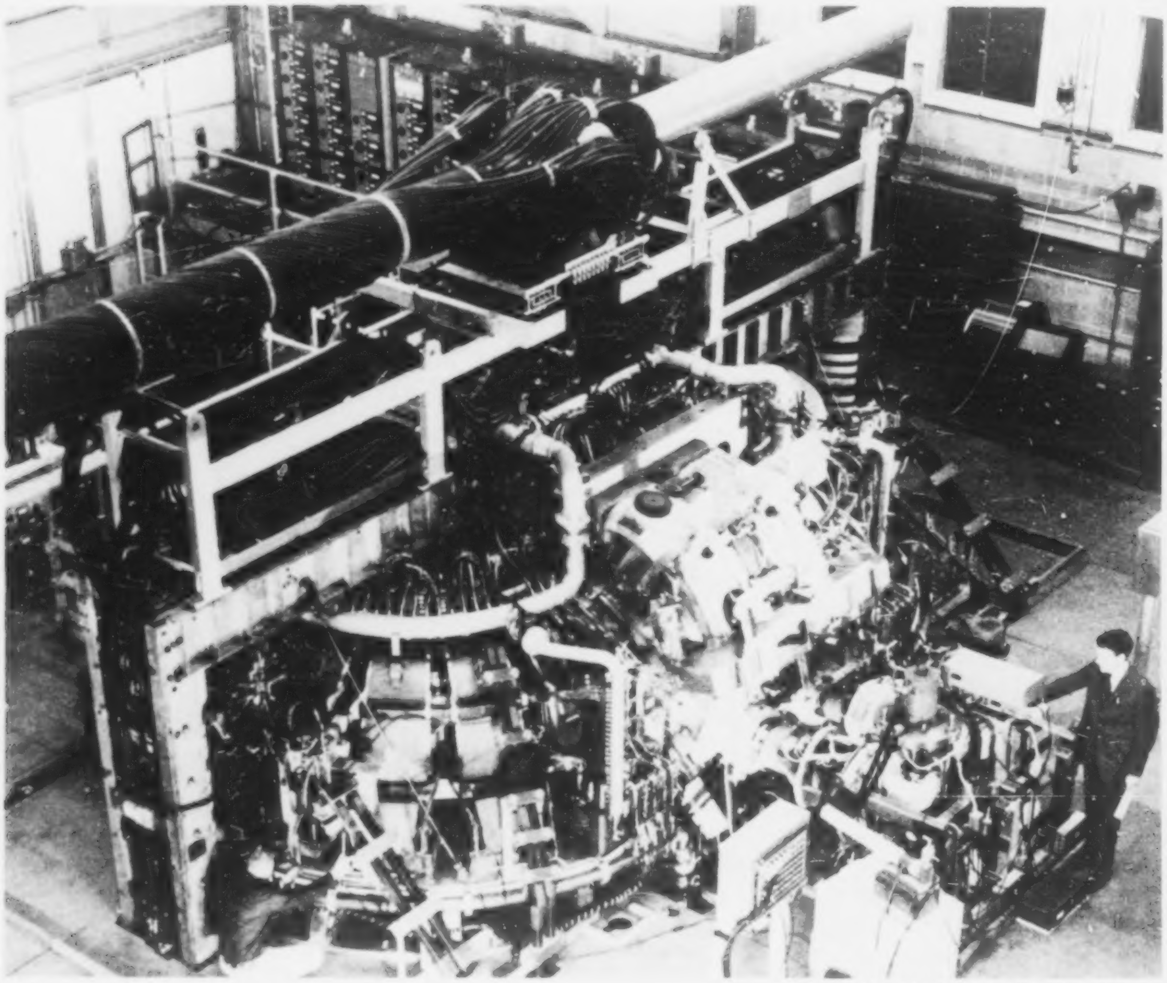

Photo credit: Princeton Plasma Physics Laboratory

Model C Stellarator at Princeton Plasma Physics Laboratory. Designed and built in the late 1950s, the Model C was converted into the United States' first tokamak in 1970.

Using a device named the "*tokamak*," a Russian acronym taken from the words for "toroidal chamber with magnetic coil," the Soviets claimed to have generated ion temperatures of 500 electron volts, electron temperatures of twice that, and a Lawson parameter of 10^{12} second-particles per cubic centimeter.

The Soviet announcement both excited and troubled the U.S. fusion community. U.S. program administrators worried that the Soviet Union would beat the United States to demonstrating fusion's feasibility. Some U.S. scientists submitted proposals to build tokamaks in the United States, while others argued that previous plans to upgrade existing devices were more important. Many scientists were skeptical of Soviet data, contending that it was ambiguous and not sufficiently compelling to change the emphasis of the U.S. program.

Early in 1969, the director of the Soviet fusion effort invited a British team of scientists to bring its own diagnostic equipment to Moscow to verify

Soviet research results. During the summer of 1969, the British team in Moscow announced its preliminary findings: the Soviet results were genuine, and, in fact, the tokamak performed even better than the Soviets had claimed. This announcement came shortly after the American scientific community had decided to convert the premier Princeton machine, the Model C stellarator, into a tokamak. In addition, funds had been allocated for the development of another tokamak at Oak Ridge National Laboratory. After publication of the British findings, the U.S. program launched three more experimental tokamaks.

The 1970s: Rapid Growth

With the identification of the tokamak as the confinement concept most likely to reach reactor-level conditions, the U.S. fusion program grew rapidly. Between 1972 and 1979, the fusion program's budget increased more than tenfold. Three forces spurred this growth. First, uncertainty over long-range energy supply mobilized public concern for finding new energy technologies. Second, fusion energy, with its potentially inexhaustible fuel supply, looked especially attractive. Third, the growth of the environmental movement and increasing opposition to nuclear fission technology drew public attention to fusion as an energy technology that might prove more environmentally acceptable. The fusion program capitalized on this public support; program leadership placed a very high priority on developing a research plan that could lead to a demonstration reactor.

From Research to Development?

The emphasis on building a demonstration reactor dramatically changed the fusion program. Previous fusion program plans had called for "breakeven-equivalent" to be demonstrated in a device containing only deuterium, to avoid the complications introduced by use of tritium.[17] The new plans called for an experiment fueled with deuterium and tritium (D-T), which would reach breakeven by actually generating fusion power.

During much of the 1970s, the director of the fusion program was largely responsible for reorienting the program toward the use of tritium in an experimental device. He sought to attain breakeven with tritium for a number of reasons:[18]

- **Physics.** The energy released in actual fusion reactions involving tritium introduced a new complication in device operation that could significantly affect experimental behavior. The director thought it was essential to study the physical consequences of releasing fusion energy in a plasma.
- **Psychology.** He also believed that too many fusion scientists were interested in plasma physics as a research enterprise, not as an energy technology. Burning D-T, he thought, would force them to come to grips with the realities of fusion power instead of the abstractions of plasma physics.
- **Engineering.** A D-T experiment would increase the amount of attention given to the engineering aspects of a fusion reactor, departing from the near-total emphasis on plasma physics in fusion research to date.
- **Politics.** A D-T experiment would generate actual fusion power for the first time. This demonstration would dramatize to the public the capabilities of fusion in a more direct way than simply achieving "breakeven-equivalent" conditions.[19] Moreover, this demonstration had to take place soon enough so that the fission breeder reactor would not become established as the long-run energy option of choice.

Many members of the fusion community opposed a D-T machine. They questioned whether the scientific principles underlying tokamak operation were sufficiently known to take such a major step. Moreover, many felt that it was not necessary to construct an experiment at this point in the research program that would involve radioactivity and thus more complications and more expense.

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[17] Tritium is radioactive and difficult to work with. More significantly, its use in fusion experiments generates neutrons that make materials in the device radioactive.

[18] Bromberg, *Fusion*, op. cit., pp. 204-205.

[19] "Breakeven-equivalent" is the attainment of plasma conditions in a deuterium-only plasma equivalent to those that, in a D-T plasma, would produce breakeven. Breakeven-equivalent does not require use of radioactive tritium and does not produce the neutron radiation generated in a breakeven D-T plasma.

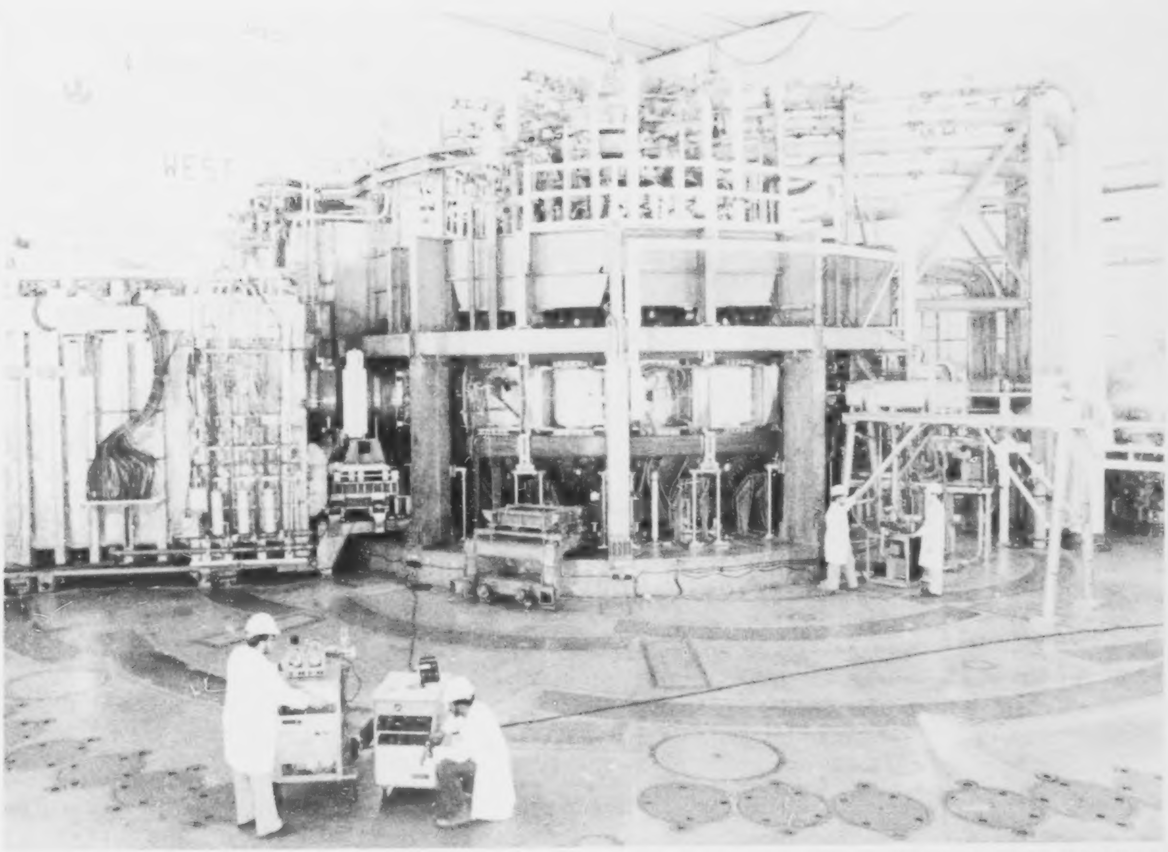

Photo credit: Princeton Plasma Physics Laboratory

The Tokamak Fusion Test Reactor at Princeton Plasma Physics Laboratory.

In mid-1973, senior fusion researchers, fusion program managers, and outside observers evaluated the plans to accelerate building a D-T machine. They concluded: 1) that scientific questions should be answered in deuterium experiments, which would be simpler and cheaper to build than machines using tritium, but 2) that a tritium-burning experiment should be conducted on an accelerated schedule.

During this period, congressional and public concern about energy supply was increasing, and, in June 1973, President Nixon announced his intention to nearly double the budget proposed for energy research over the next 5 years. By June 1974, the funding increases necessary to pursue accelerated development of fusion were appropriated. Planning began for a D-T burning breakeven experiment, the Tokamak Fusion Test Reactor (TFTR), to be constructed at the Princeton Plasma Physics Laboratory.

Program organization also changed when Congress abolished the AEC in 1974 and transferred its energy research programs to the Energy Research and Development Administration. ERDA was a new agency with a broad mission in energy research. It assumed management of AEC's nuclear fission and fusion programs, as well as programs in solar and renewable technologies, fossil fuels, and conservation.

Concept Competition

The expansion of the tokamak program increased competition for funds among proponents of alternate confinement concepts. Most fusion community leaders believed that the fusion program could not command the budget required to construct more than one additional TFTR-class experiment. Thus, there was some concern about the role of the three remaining major fusion laboratories. Oak Ridge National Laboratory, which had competed unsuccessfully with Princeton to construct the tokamak breakeven experiment, had tokamak experience that would be needed to support the Princeton experiment. The future was more uncertain for the non-tokamak research programs at Los Alamos and Lawrence Livermore national laboratories.

Between the major concepts investigated at these two labs, the "magnetic mirror" at Livermore was selected over the "theta pinch" at Los Alamos to become the principal alternative to the tokamak. Livermore had constructed a series of mirror devices during the 1960s and 1970s, and, in 1976, its proposal to build a greatly scaled-up Mirror Fusion Test Facility (MFTF) was approved. After design and construction of MFTF were underway, researchers developed a design innovation that could improve the performance of the mirror concept. This idea was tested by building the Tandem Mirror Experiment (TMX) and found to be valid. Even so, the improvement was too small to justify changing the MFTF design, so construction proceeded as originally planned.

Livermore scientists then proposed another innovation that seemed to have the potential to make a mirror reactor a viable competitor to a tokamak reactor. This time, the gain appeared to be sufficiently great to warrant modifying the MFTF design, more than tripling its size. Moreover, Livermore scientists had so much confidence in the theory that they proposed to start modifications to MFTF before testing the new concept experimentally. In 1979, they proposed to modify both TMX and MFTF in parallel, with the smaller TMX-Upgrade (TMX-U) to be completed and operated to verify the new concept at a time when substantial work still remained to be done on the revised MFTF (now called MFTF-B). In this way, any changes found to be necessary as a result of tests on TMX-U could be incorporated directly into MFTF-B during its construction. Construction of MFTF-B began in 1981.

Systems Studies

In addition to experiments on confinement concepts, fusion program managers in the 1970s began to consider design attributes of fusion reactors in a systematic way. Scientists and engineers began to address the engineering problems that various confinement methods posed for reactor design, and "reactor relevance" soon became a driving force for additional research. Sustained and serious interest in these design studies, also called *systems studies*, attracted the attention of people outside the fusion community. Several individuals in electric utilities began to follow fusion closely, and the utility research consortium, the Electric Power Research Institute (EPRI), established a Fusion Advisory Committee.

World Effort

During the 1970s, the U.S. fusion program led the world. It had the greatest breadth and depth of confinement concepts under investigation, and its attention to fusion systems and technology was unmatched. However, programs in the Soviet Union, Japan, and Western Europe grew during the 1970s. Each program made plans to build a TFTR-class tokamak to reach breakeven-equivalent conditions: the Joint European Torus (JET) in Europe, JT-60 in Japan, and the T-15 tokamak in the Soviet Union. All of these machines except the T-15 are now operational. The international aspects of fusion research are discussed more fully in chapter 7.

Program Reorientation

In 1977, President Carter incorporated the functions of ERDA, including the fusion program, into a new agency, the Department of Energy. DOE deemphasized support for nuclear fission, primarily due to concern over the proliferation aspects of breeder reactors, and it increased support for solar energy, conversion from oil and gas to coal, and conservation.[20]

The first director of the DOE Office of Energy Research believed that the budget for the fusion program was too large for fusion's uncertain prospects. In his capacity as scientific advisor to the

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[20] Bromberg, *Fusion*, op. cit., p. 235.

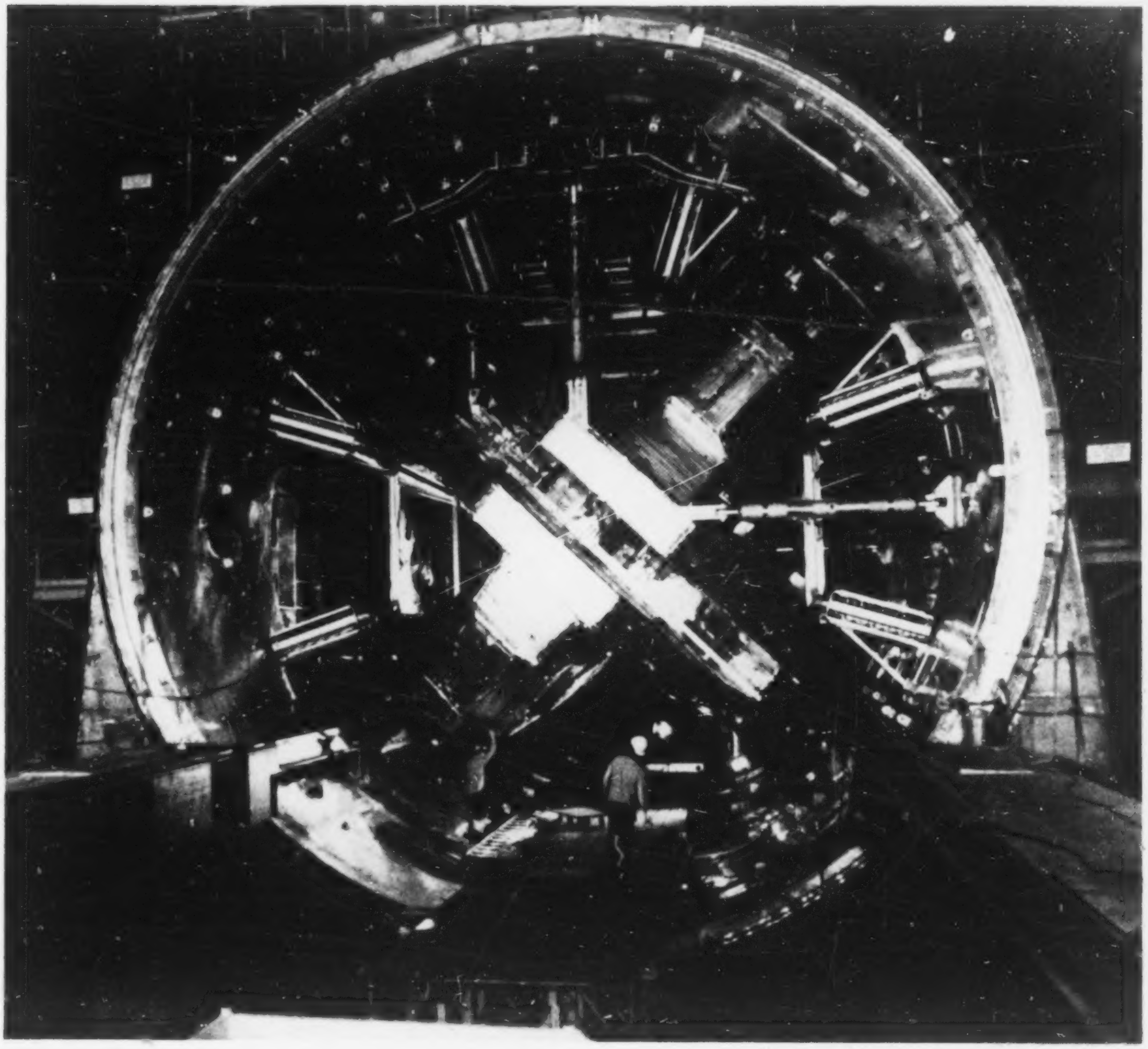

Photo credit: Lawrence Livermore National Laboratory

Installation of one of the end cell magnets for MFTF-B. Another view of this magnet is shown on p. 87.

Secretary of Energy, he commissioned a high-level outside review of the program, a review that he expected would recommend cutting the budget and relaxing the program's emphasis on an early demonstration reactor.[21] On the contrary, the review panel praised the management and scientific achievements of the fusion program and did not recommend budget cuts. Mostly as a result of the panel's findings, the Secretary of Energy subsequently reaffirmed the near-term planning of the fusion program. With few modifications, DOE management supported maintaining current budget levels, pushing towards early completion and operation of TFTR, maintaining ongoing fusion system studies, and accelerating fusion technology development.

Although the short-term fusion program plans continued much as before, the long-term strategy under DOE in the late 1970s differed from the ERDA strategy earlier in the decade. The review panel stated in its report that "the first objective of the program must be to determine the highest potential of fusion as a practical source of energy." This meant not proceeding with construction of a tokamak device to succeed TFTR until "a convincing case should be made that Tokamaks can be engineered into attractive energy producers."[22] In effect, the committee recommended that the tokamak program be held up at the TFTR stage until other devices, such as the mirror, could be compared to it at relatively equivalent stages of development.

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[21] Ibid., p. 236.

Under DOE, the fusion program did not have the sense of urgency that was so important earlier in the decade. Fusion could not mitigate the short-term oil and gas crisis facing the United States. Furthermore, as a potentially inexhaustible long-range energy source (along with solar energy and the fission breeder reactor), fusion was not thought needed until well into the next century. Therefore, there appeared to be no compelling reasons to develop a fusion demonstration plant rapidly.[23]

The 1980s: Leveling Off

The fusion program has continued to make substantial technical progress during the 1980s. Several world machines have the potential to achieve breakeven, or breakeven-equivalent conditions, within the decade; in addition, significant advances in plasma physics and fusion technology continue.[24]

ERAB Review of the Fusion Program, 1980

In 1980, the Energy Research Advisory Board (ERAB), a standing committee that advises the Secretary of Energy, established a committee to review DOE's fusion program. The committee's report evaluated technical progress in the fusion program over the previous few years and found many accomplishments that justified the panel's confidence that breakeven was near. The panel concluded that:

> . . . the United States is now ready to embark on the next step toward the goal of achieving economic fusion power: Exploration of the engineering feasibility of fusion.[25]

The panel proposed that the program begin planning a Fusion Engineering Device (FED), which would provide a focus for development of reactor-relevant technologies and components, enable researchers to evaluate safety issues associated with fusion power, and facilitate investigation of additional plasma physics issues. This device would be built and operated as part of a broad program of engineering experimentation and analysis to be conducted by a new fusion engineering center. The ERAB panel recognized that planning and constructing FED would require a doubling of the fusion budget over the next 5 to 7 years, and it recommended this budget increase.

The Magnetic Fusion Energy Engineering Act, 1980

Many of the recommendations of the ERAB panel were incorporated into the Magnetic Fusion Energy Engineering Act (MFEE Act), passed by Congress in September 1980.[26] Passage of the MFEE Act was largely a result of Representative Mike McCormack's (D-Washington) efforts. It urged acceleration of the national effort in magnetic fusion research, development, and demonstration activities. Like the ERAB report, the act recommended creation of a Magnetic Fusion Engineering Center to coordinate major magnetic fusion engineering devices.

The MFEE Act recommended that funding levels for magnetic fusion be doubled (in constant dollars) within 7 years. However, it did not appropriate these increases, and there was no follow-up. In effect, the act indicated that Congress considered the fusion program worthwhile and deserving of support but was unable or unwilling to make a long-term commitment to substantially increase expenditures. Actual appropriations in the 1980s did not grow at the level specified in the act and in fact continued the drop in constant dollar funding that began in 1977.

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[22] Foster Committee, Final Report (DOE/ER-0008, June 1978). Quoted in T.A. Heppenheimer, *The Man-Made Sun*, op. cit., pp. 201-202.

[23] Bromberg, *Fusion*, op. cit., p. 247.

[24] Many of the technical accomplishments in the fusion program and the tasks still to be done are discussed in ch. 4 of this assessment.

[25] "Report on the Department of Energy's Magnetic Fusion Program," prepared by the Fusion Review Panel of the Energy Research Advisory Board, August 1980, as quoted in *Fusion Energy: An Overview of the Magnetic Confinement Approach, Its Objectives, and Pace*, a report prepared for the Subcommittee on Energy Research and Production, House Committee on Science and Technology, 96th Cong., 2d sess., Serial GGG, December 1980, p. 133.

[26] Public Law 96-386, signed into law on Oct. 7, 1980.

Reagan Administration Budgets and Philosophy

Energy R&D budgets underwent radical cuts in 1981 at the beginning of the Reagan Administration. The Reagan Administration stated that development activity belonged in the private sector and that the government could encourage this activity most effectively by staying out of it. Accordingly, DOE research budgets for solar energy, fossil fuel technology, fission technology, and energy conservation—those energy areas most heavily weighted towards development or demonstration, as opposed to research—were substantially reduced. In contrast, the Reagan Administration continued to support government funding for long-term, high-risk programs—e.g., fusion research—that would not attract private investment. Therefore, although the fusion research budget has decreased in the 1980s, it has not been cut as severely as some of DOE's other energy R&D programs.

With annual budget appropriations falling, the ambitious plans of the 1970s, which culminated in the MFEE Act of 1980, could not be implemented. Thus, the fusion program has had to modify its program strategy; subsequent plans attempted to identify the most important aspects of the fusion program to pursue.

The Comprehensive Program Management Plan, 1983

The MFEE Act required that the Secretary of Energy prepare a Comprehensive Program Management Plan (CPMP) outlining the fusion program's strategy and schedule. This plan was completed by DOE and transmitted to Congress in 1983.[27] The CPMP attempted to satisfy the emphases of the MFEE Act within the fiscal constraints imposed by the Reagan Administration. The plan also sought to preserve the role of international leadership in fusion for the United States.

The CPMP had a clear reactor emphasis, but it was also consistent with Reagan Administration philosophy towards development. The plan explicitly ruled out government construction of a demonstration reactor, stating that:

> The primary objectives of the [fusion] program are designed to provide a technical basis for decisions by the private sector on whether to proceed with the commercial development of fusion energy. Proceeding with a Federally funded demonstration plant is not part of this plan.[28]

The CPMP stated that within the next decade, the fusion program would select a plasma confinement concept to undergo further development as a power reactor core. The plan defined two stages that would permit a decision to be made to build a demonstration reactor by the year 2000.

ERAB Review of the Fusion Program, 1983

An additional provision of the MFEE Act established a technical panel on magnetic fusion as an ERAB subcommittee. The subcommittee was mandated to conduct a triennial review of the fusion program, with the first such review to be conducted in 1983.

The subcommittee's report[29] recognized that budgetary constraints had made it impossible to accomplish the goals of the MFEE Act on the timescale envisioned. The panel recommended that DOE abandon the CPMP, stating that it would force the program to make a choice between tandem mirror and tokamak confinement concepts before constructing another major device, a choice that in turn would require delaying progress on the tokamak. The panel also noted that the CPMP's schedule called for construction of a next-generation engineering test reactor—a major facility intended to explore engineering aspects of fusion—before necessary technology development could be completed.

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[27] *Comprehensive Program Management Plan (CPMP) for Magnetic Fusion Energy*, June 1983. Submitted to the House Science and Technology Committee by the Secretary of Energy pursuant to the Magnetic Fusion Energy Engineering Act.

[28] Ibid., p. 2.

[29] Energy Research Advisory Board, *Magnetic Fusion Energy Research and Development*, Final Report prepared by the Technical Panel on Magnetic Fusion of the Energy Research Advisory Board, DOE/S-0026, January 1984.

As a revised program strategy, the ERAB panel recommended that a tokamak follow-up device to TFTR be built to study scientific issues. The panel recommended that the reactor engineering efforts be postponed until additional resources were available, and that a strong and innovative base program be maintained in plasma physics, technology development, and alternative confinement concepts.

The Magnetic Fusion Program Plan, 1985

DOE revised its program plan in response to the criticisms of the ERAB subcommittee. In 1985, DOE issued the Magnetic Fusion Program Plan (MFPP), which stated that "the goal of the magnetic fusion program is to establish the scientific and technological base required for fusion energy."[30] Unlike the CPMP, however, the MFPP lessened the reactor emphasis, concentrated more on the science and engineering requirements, and relaxed the schedule for fusion development:

> The schedule for completing magnetic fusion development is directly related to the technical, economic, and political uncertainties associated with energy supply, which are likely to exist for several decades. The Magnetic Fusion Program Plan is a strategy for solving fusion's technical problems within a time frame keyed to resolution of other areas of energy development.[31]

Like the CPMP, the MFPP did not extend to construction of a fusion demonstration reactor. The plan laid out key technical issues that must be resolved by the fusion program and set out a goal of international collaboration, rather than international leadership, for the U.S. fusion program.

ERAB Review of the Fusion Program, 1986

The second triennial review of the magnetic fusion program was completed by the ERAB subcommittee on magnetic fusion in November 1986.[32] The subcommittee endorsed the fusion program's direction, strategy, and plan and reaffirmed the need to investigate fusion energy as "an attractive energy source of great potential for the future." The panel specifically considered two issues of great importance to the future direction of the program: 1) the construction of a Compact Ignition Tokamak (CIT) as an experiment that would extend scientific understanding beyond that obtainable in TFTR; and 2) the role of international collaboration in an engineering test reactor project.

The Compact Ignition Tokamak.—Several years of TFTR operation have shown continued progress both in understanding and in achieving confinement. TFTR has attained Lawson parameters above 10^{14} second-particles per cubic centimeter (a factor of 10,000 improvement over 1950's results) and ion temperatures of 20,000 electron volts (a factor of 200 improvement). Attainment of actual breakeven when tritium is introduced seems highly probable, and the fusion community has been actively exploring options for a next step beyond TFTR. This has led to DOE recommendations for CIT construction.

CIT will explore the physics associated with ignited plasmas. The ERAB subcommittee concluded that CIT is "an essential and timely project,"[33] both because it will address a fundamental physics issue and because it will provide technical information and experience valuable to the engineering test reactor. ERAB recommended providing an increment to the magnetic fusion program budget to prevent funding for CIT from being taken from other program areas. The construction cost of CIT, in 1986 dollars, has been estimated at $300 million for the facility, plus about $60 million for diagnostic equipment and associated R&D. This estimate assumes that the facility will be located at Princeton Plasma Physics Laboratory, where, according to DOE, site credits will save about $200 million.[34]

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[30] U.S. Department of Energy, Office of Energy Research, *Magnetic Fusion Program Plan*, DOE/ER-0214, February 1985, Executive Summary.

[31] Ibid.

[32] Energy Research Advisory Board, *Report of the Technical Panel on Magnetic Fusion of the Energy Research Advisory Board*, prepared for the U.S. Department of Energy, November 1986.

[33] Ibid., p. 1.

The Role of International Collaboration.—The subcommittee endorsed current DOE efforts in international collaboration. In particular, the panel supported the idea of constructing an international engineering test reactor. As envisioned, this device—called the International Thermonuclear Experimental Reactor (ITER)—will be a large experimental facility designed to explore engineering and technological issues relevant to fusion reactors. The ERAB subcommittee stated that "the United States should consider reaching out to other nations to establish a multinational structure for fusion relationships."[35] However, ERAB also recognized the inherent complexity and uncertainty of major international collaborations, pointing out that "some realistic consideration must be given to the possibility that international collaboration on a large scale may not come about."[36] At present, DOE is investigating the potential of undertaking a joint planning activity with the other major fusion powers on a conceptual design for ITER, along with supporting R&D.

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[34] Ibid., p. 11. Site credits refer to the savings that result from constructing the project at a location that already has some of the needed equipment in place. By constructing CIT at Princeton, the experiment will be able to take advantage of the existing TFTR power supplies and other equipment.

[35] Ibid., p. 14.

[36] Ibid., p. 17. A detailed discussion of international collaboration on ITER and other projects can be found in ch. 7 of this assessment.

Chapter 4

Fusion Science and Technology

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Chapter 4

Fusion Science and Technology

Great progress has been made over the past 35 years of fusion research. Nevertheless, many scientific and technological issues have yet to be resolved before fusion reactors can be designed and built. Fundamental questions in plasma science remain, especially involving the behavior of plasmas that actually produce fusion power. Other plasma science questions involve the behavior and operation of the various *confinement concepts* that might be used to hold fusion plasmas.

To date, engineering issues have not been studied as extensively as plasma science issues. For many years, engineering studies were deferred for lack of funds; science had a higher funding priority. In addition, fusion technologies that require a source of fusion power to be tested and developed have had to await a device that could supply the power. Until recently, the fusion science database has not been sufficient to permit such a device to be designed with confidence.

This chapter discusses the various confinement concepts under study, the systems required in a fusion reactor, and the issues that must be resolved before such systems can be built. It then outlines the research plan required to resolve these issues and estimates the amount of time and money that such a research plan will take.

CONFINEMENT CONCEPTS[1]

Most of the fusion program's research has focused on different magnetic confinement concepts that can be used to create, confine, and understand the behavior of plasmas. In all of these concepts, magnetic fields are used to confine the plasma; the concepts differ in the shape of the fields and the manner in which they are generated. These differences have implications for the requirements, complexity, and cost of the engineering systems that surround the plasma. Table 4-1 lists the principal confinement schemes presently under investigation in the United States and classifies them according to their level of development. The concepts are described in the following section.

At this stage of the research program, it is not known which confinement concept can best form the basis of a fusion reactor. The tokamak is much more developed than the others, and tokamaks are expected to demonstrate the basic scientific requirements for fusion within a few years. However, several alternate concepts are under investigation in order to gain a better understanding of the confinement process and to explore possibilities for improving reactor performance.

Table 4-1.—Classification of Confinement Concepts

Well-developed knowledge base	Moderately developed knowledge base	Developing knowledge base
Conventional tokamak	Advanced tokamak Tandem mirror Stellarator Reversed-field pinch	Spheromak Field-reversed configuration Dense Z-pinch

SOURCE: Adapted from Argonne National Laboratory, Fusion Power Program, *Technical Planning Activity: Final Report*, commissioned by the U.S. Department of Energy, Office of Fusion Energy, ANL/FPP-87-1, January 1987, p. 15.

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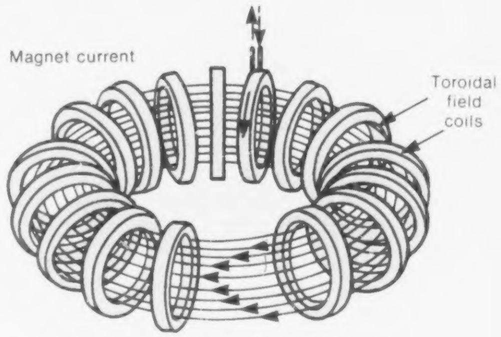
[1] This chapter discusses only magnetic confinement approaches. Other approaches to fusion are discussed in app. B. The concepts mentioned in this section are described in greater detail in pp. 156-204 of *Physics Through the 1990s: Plasmas and Fluids*, by the National Research Council (Washington, DC: National Academy Press, 1986).

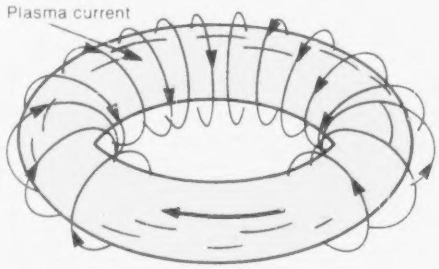
The major scientific questions to be answered for each confinement approach are whether and with what confidence the conditions necessary for a sustained, power-producing fusion reaction can be simultaneously satisfied in a commercial-scale reactor. Much of the experimental and theoretical work in confinement studies involves the identification and testing of *scaling relationships* that predict the performance of future devices from the results of previous experiments. Ideally, such scaling models should be derivable from the basic laws of physics. However, the behavior of plasmas confined in magnetic fields is so complicated that a general theory has not yet been found. With some simplifying assumptions, limited theoretical models have been developed, but they are not broad enough to extrapolate the behavior of a concept to an unexplored range. Without a sound theoretical base, the risk of taking too large a step is great. A series of intermediate-scale experiments is needed to bridge the gap between concept development and a full-scale reactor.

Even with the tokamak—the most studied confinement concept—scaling properties are not fully understood. **Although tokamaks have attained by far the best experimental performance of any confinement concept, no proven theoretical explanation of how that performance scales with parameters such as size, magnetic field, and plasma current has yet been derived.** Without a complete theoretical basis, "empirical" scaling relationships deduced from past observations must be used. Such empirical relationships may well prove sufficient for designing a machine capable of forming reactor-scale plasmas before a fundamental theoretical understanding of tokamak behavior is reached.

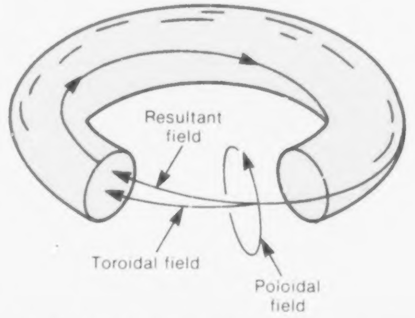
Figure 4-1.—Tokamak Magnetic Fields



Toroidal field—due to external magnets



Poloidal field—due to plasma current



SOURCE: Princeton Plasma Physics Laboratory, Information Bulletin NT-1: Fusion Power, 1984, p. 4

"Closed" Concepts

In "closed" magnetic confinement configurations, the plasma is contained by magnetic lines of force that do not lead out of the device. Closed configurations all have the basic shape of a doughnut or inner tube, which is called a "*torus*." A magnetic field can encircle a torus in two different directions (figure 4-1). A field running the long way around the torus, in the direction that the tread runs around a tire, is called a "toroidal" field. This field is generally created by external magnet coils, called toroidal field coils, through which the plasma torus passes. A magnetic field perpendicular to the toroidal field, encircling the torus the short way, is called a "poloidal" field. This field is generated by electrical currents induced to flow within the plasma itself. Together, toroidal and poloidal magnetic fields form the total magnetic field that confines the plasma.

Conventional Tokamak

In a tokamak, the principal confining magnetic field is toroidal, and it is generated by large external magnets encircling the plasma. This field alone, however, is not sufficient to confine the plasma. A secondary poloidal field, generated by plasma currents, is also required. The combination of poloidal and toroidal fields produces a total field that twists around the torus and is able to confine the plasma (figure 4-1).

The tokamak concept was developed in the Soviet Union, and, since the late 1960s, it has been the primary confinement concept in all four of the world's major fusion research programs. It has also served as the principal workhorse for developing plasma technology. The scientific progress of the tokamak is far ahead of any other concept. Major world tokamaks are listed in table 4-2.

Advanced Tokamak

Various features now under investigation may substantially improve tokamak performance. Modifying the shape of the plasma cross-section can increase the maximum plasma pressure that can be confined with a given magnetic field. The Doublet III-D (D III-D) tokamak at GA Technologies and the Princeton Beta Experiment Modification (PBX-M) tokamak at Princeton Plasma Physics Laboratory are being used to investigate shaped plasmas according to this principle. Other variants on tokamak design would permit more compact fusion cores to be constructed, which could lead to less expensive reactors; these improvements are under study.

Still other improvements would permit tokamaks to run continuously. The technique typically used today to drive the plasma current in a tokamak can be run only in pulses. Technologies for driving continuous, or steady-state, plasma currents are being investigated at a number of different experimental facilities.

Stellarator

The stellarator is a toroidal device in which both the toroidal and poloidal confining fields are generated by external magnets and do not depend on electric currents within the plasma. The external magnets are consequently more complicated than those of a tokamak (figure 4-2). However, the absence of plasma current in a stellarator enables steady-state operation to be achieved more directly without the need for current drive.

The stellarator concept was invented in the United States. After the discovery of the tokamak in the late 1960s, however, the United States converted its stellarators into tokamaks. The stellarator concept was kept alive primarily by research

Table 4-2.—Major World Tokamaks[a]

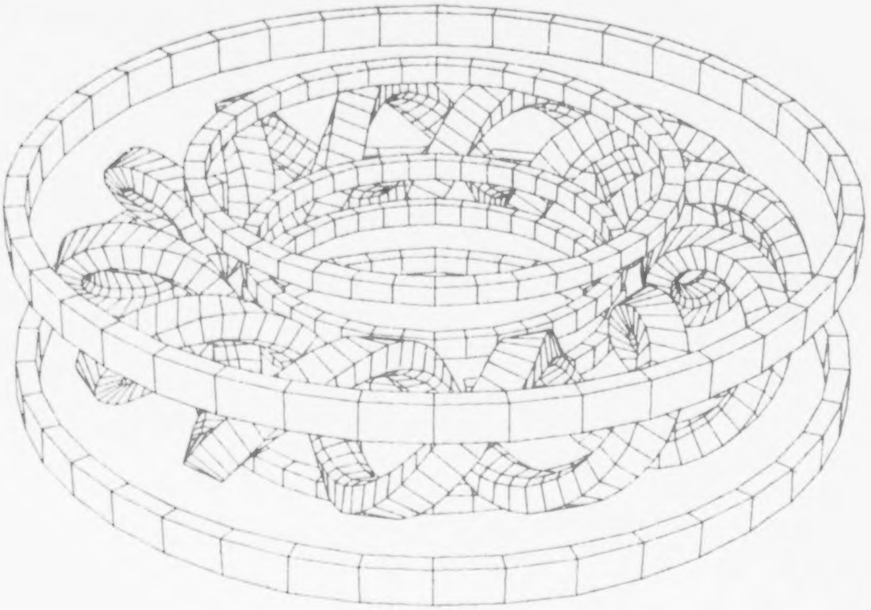
Device	Location	Status
JET	European Community (United Kingdom)	Operating
D III-D	United States (GA Technologies)	Operating
Alcator C-Mod	United States (MIT)	Under construction
T-14	U.S.S.R. (Kurchatov)	Under construction
TFTR	United States (PPPL)	Operating
JT-60	Japan (Naka-machi)	Operating
T-15	U.S.S.R. (Kurchatov)	Under construction
ASDEX-Upgrade	Federal Republic of Germany (Garching)	Under construction
Tore Supra	France (Cadarache)	Under construction
Frascati Tokamak Upgrade	Italy (Frascati)	Under construction
PBX-M	United States (PPPL)	Under construction
TEXTOR	Federal Republic of Germany (Jülich)	Operating

[a] Listed in decreasing order of plasma current, one of the many parameters that determines tokamak capability. No single factor by itself measures capability well; current is used here only to give a rough distinction between those devices at the top of the list and those at the bottom. Ranking by size, magnetic field, or other parameter would rearrange the list somewhat.

NOTE: This table includes only the largest tokamaks. The *World Survey of Activities in Controlled Fusion Research, 1986 Edition* (published in *Nuclear Fusion*, Special Supplement 1986) lists a total of 77 existing and proposed tokamaks at 54 sites in 26 countries.

SOURCE: Office of Technology Assessment, 1987.

Figure 4-2.—Magnet Coils for the Advanced Toroidal Facility, A Stellarator



SOURCE: Oak Ridge National Laboratory

in the Soviet Union, Europe, and Japan, and, due to good results, the United States has recently revived its stellarator effort. Stellarators today perform as well as comparably sized tokamaks.

Major world stellarator facilities that are operating or under construction are listed in table 4-3. Not shown on the table is the Large Helical System proposed to be built in Japan at a cost several times that of the largest stellarator machine now under construction; if built and operated, the new Japanese device would be the largest operational non-tokamak fusion experiment.

Reversed-Field Pinch

In a reversed-field pinch, the toroidal magnetic field is generated primarily by external magnets and the poloidal field primarily by plasma currents. The toroidal and poloidal fields are comparable in strength, and the toroidal field reverses direction near the outside of the plasma, giving

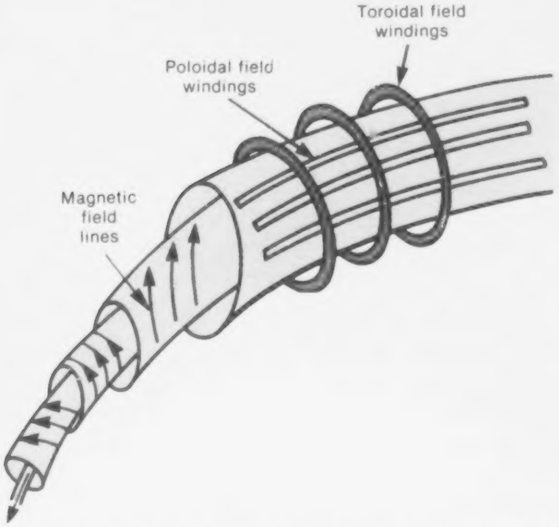
Table 4-3.—Major World Stellarators[a]

Device	Location	Status
ATF	United States (ORNL)	Under construction
Wendelstein VII-AS	Federal Republic of Germany (Garching)	Under construction
URAGAN-2M	U.S.S.R. (Kharkov)	Under construction
Heliotron-E	Japan (Kyoto University)	Operating
URAGAN-3	U.S.S.R. (Kharkov)	Operating
CHS	Japan (Nagoya University)	Under construction
L-2	U.S.S.R. (Lebedev)	Operating
H-1	Australia (Canberra)	Under construction

[a] Listed in order of decreasing stored magnetic energy, a parameter which in turn depends both on magnetic field strength and plasma volume.

SOURCE: Office of Technology Assessment, 1987, from data provided by Oak Ridge National Laboratory.

Figure 4-3.—Reversed-Field Pinch



SOURCE: Adapted from National Research Council, *Physics Through the 1990s: Plasmas and Fluids* (Washington, DC: National Academy Press, 1986).

the concept its name (see figure 4-3). In a tokamak, the toroidal field dominates and points in the same direction throughout the plasma.

The reversed-field pinch generates more of its magnetic field from plasma currents and less from external magnets, permitting its external magnets to be smaller than those of a comparably performing tokamak. The nature of the magnetic fields in a reversed-field pinch may also permit steady-state plasma currents to be driven in a much simpler manner than is applicable in a tokamak. Moreover, a reversed-field pinch plasma may be able to heat itself to reactor temperatures without the complex and costly external heating systems required by tokamaks.

Los Alamos National Laboratory in New Mexico is the center of U.S. reversed-field pinch research. The Confinement Physics Research Facility (CPRF) to be built there will hold the largest reversed-field pinch device in the United States. A variant of the reversed-field pinch, the Ohmically Heated Toroidal Experiment, or OHTE, was built at GA Technologies in San Diego, California. Reversed-field pinch research is also conducted in both Europe and Japan. Table 4-4 lists the major world reversed-field pinches.

Spheromak

The spheromak is one of a class of less developed confinement concepts called "compact toroids," which do not have toroidal field coils linking the plasma loop and therefore avoid the engineering problem of constructing rings locked within rings. Conceptually, if the torodial field coils and inner walls of a reversed-field pinch were removed and the central hole were shrunk to nothing, the resultant plasma would be that of the spheromak. Its overall shape is spherical; although the internal magnetic field has both toroidal and poloidal components, the device has no central hole or external field coil linking the plasma (figure 4-4). The plasma chamber lies entirely within the external magnets. If the spheromak can progress to reactor scale, its small size and simplicity may lead to considerable engineering advantages. However, the present state of knowledge of spheromak physics is rudimentary.

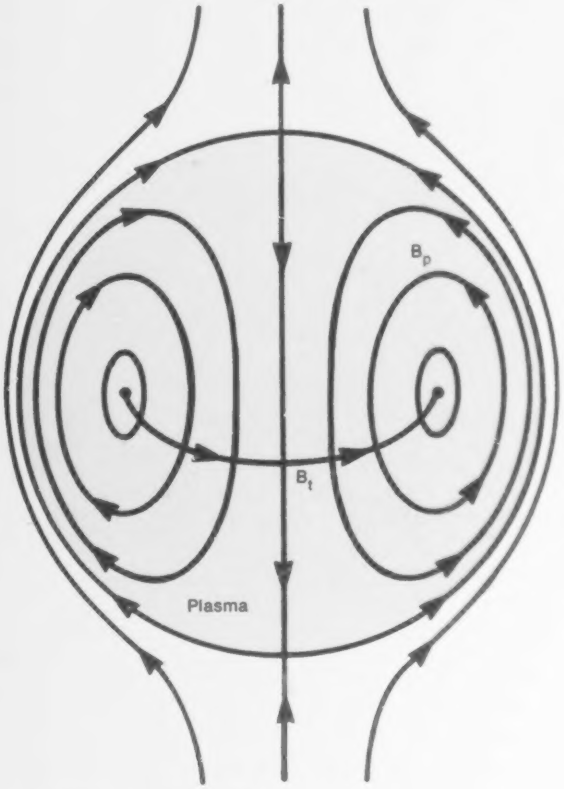
Table 4-4.—Major World Reversed-Field Pinches[a]

Device	Location	Status
CPRF	United States (LANL)	Under construction
RFX	Italy (Padua)	Under construction
OHTE	United States (GA Technologies)	Operating
HBTX 1-B	United Kingdom (Culham)	Operating
ZT-40M	United States (LANL)	Operating
MST	United States (University of Wisconsin)	Under construction
ETA BETA II	Italy (Padua)	Operating
Repute 1	Japan (Tokyo University)	Operating
TPE-1RM(15)	Japan (Tsukuba University)	Operating
STP-3M	Japan (Nagoya University)	Operating

[a] Listed in order of decreasing plasma current, a rough measure of reversed-field pinch performance.

SOURCE: Office of Technology Assessment, 1987; from data supplied by the Los Alamos National Laboratory.

Figure 4-4.—Spheromak



B_p = Poloidal magnetic field

B_t = Toroidal magnetic field

SOURCE: M.N. Rosenbluth and M.N. Bussac, "MHD Stability of Spheromak," *Nuclear Fusion* 19(4):489-498 (Vienna, Austria: International Atomic Energy Agency, 1979).

Spheromak research at Los Alamos National Laboratory was terminated in 1987 due to fiscal constraints, and another major U.S. device at Princeton Plasma Physics Laboratory is to be terminated in fiscal year 1988. The remaining U.S. spheromak research effort takes place at the University of Maryland. Spheromaks also are being studied in Japan and the United Kingdom. Major world spheromak devices are listed in table 4-5.

Field-Reversed Configuration

The field-reversed configuration (FRC) is another form of compact toroid. Despite the similar name, it does not resemble the reversed-field pinch. It is unusual among closed magnetic confinement concepts in providing confinement with only poloidal fields; the FRC has no toroidal field. The plasma is greatly elongated in the poloidal direction and from the outside has a cylindrical shape (figure 4-5).

Like the spheromak, the FRC does not have external magnets penetrating a hole in its center; all the magnets are located outside the cylindrical plasma. The FRC also has the particular virtue of providing extremely high plasma pressure for a given amount of magnetic field strength. If its confining field is increased in strength, the FRC plasma will be compressed and heated. Such heating may be sufficient to reach reactor conditions, eliminating the need for external heating. Existing FRC plasmas are stable, but whether stability can be achieved in reactor-sized FRC plasmas is uncertain. A new facility, LSX, is under construction at Spectra Technologies in Bellevue, Washington, to investigate the stability of larger plasmas.

U.S. FRC research started at the Naval Research Laboratory in Washington, D.C., in the late 1960s. Increased effort in the United States in the late 1970s, centered at Los Alamos, was undertaken largely in response to experimental results obtained earlier in the decade from the Soviet Union

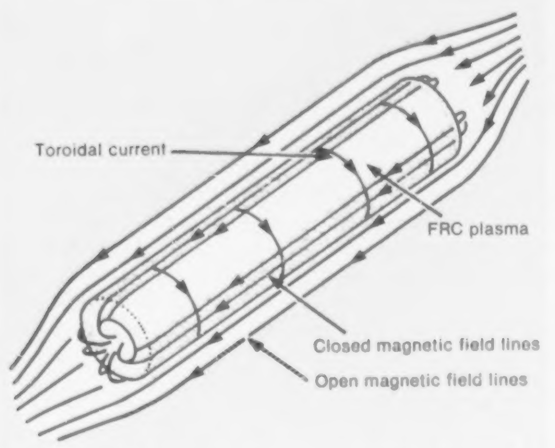
Table 4-5.—Major World Spheromaks[a]

Device	Location	Status
S-1	United States (PPPL)	To be terminated, fiscal year 1988
CTX	United States (LANL)	Terminated, fiscal year 1987
MS	United States (University of Maryland)	Under construction
CTCC	Japan	Operating
Manchester U.	United Kingdom (University of Manchester)	Operating
TS-3	Japan	Operating

[a] Listed approximately by decreasing order of the size of the spheromak research effort at each site; it is difficult to specify any single physical parameter as a rough measure of spheromak capability.

SOURCE: Office of Technology Assessment, 1987.

Figure 4-5.—Field-Reversed Configuration



SOURCE: National Research Council, *Physics Through the 1990s: Plasmas and Fluids* (Washington, DC: National Academy Press, 1986).

and the Federal Republic of Germany. Soviet research has continued, but German and British research programs have stopped. Meanwhile, a program in Japan has begun. Major field-reversed configuration experiments around the world are listed in table 4-6.

"Open" Concepts

Plasmas in open magnetic confinement devices are confined by magnetic fields that do not close back on themselves within the device but rather extend well outside the device. Since plasma particles can easily travel along magnetic field lines, some additional mechanism is required to reduce the rate at which plasma escapes out the ends of an open confinement device.

Magnetic Mirrors

Fusion plasmas can be confined in an open-ended tube by strengthening, and thereby compressing, the magnetic fields near the ends. Strengthening the magnetic field near the ends "reflects" plasma particles back into the center much as narrowing the ends of a sausage helps keep in the meat. However, the ends of a *simple magnetic mirror* (figure 4-6a) are not otherwise sealed. Just as the meat eventually forces its way out of an unsealed sausage when squeezed, a simple magnetic mirror cannot confine a plasma well enough to generate fusion power. In addition, simple mirrors are usually unstable, with the plasma as a whole tending to slip out sideways.

A variation of the simple mirror is the *minimum-B mirror* (figure 4-6b), one version of which uses a coil shaped like the seam on a baseball to create a magnetic field that is lowest in strength at the center and increases in strength towards the outside. Particles leaving the center tend to be reflected back by the increasing magnetic field at the outside, just as particles leaving the simple mirror tend to be reflected back at the ends. This configuration is stable, and there is no tendency for the plasma as a whole to escape. However, despite these improvements, the minimum-B mirror cannot confine a plasma well enough to generate net fusion power.

The *tandem mirror* (figure 4-6c) improves the simple magnetic mirror by utilizing additional mirrors to improve the plugging at each end. These plugs, called end cells, are themselves magnetic mirrors. Rather than trapping the main plasma, the end cells hold particles that generate an electric field. This electric field, in turn, keeps the plasma in the central cell from escap-

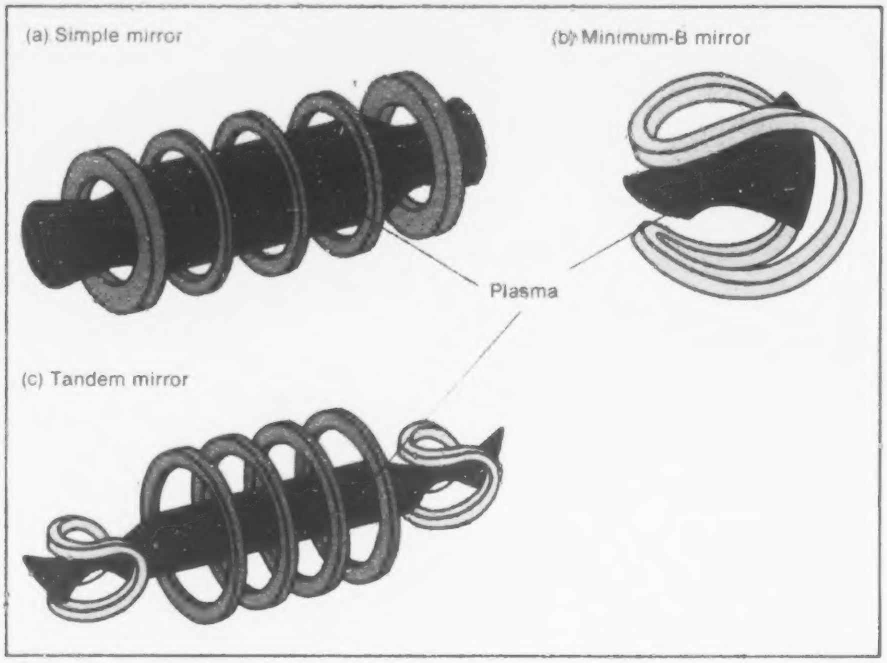
Table 4-6.—Major World Field-Reversed Configurations[a]

Device	Location	Status
LSX	United States (Spectra Technologies)	Under construction
FRX-C	United States (LANL)	Operating
BN, TOR	U.S.S.R. (Kurchatov)	Operating
TRX-2	United States (Spectra Technologies)	Operating
OCT, PIACE	Japan (Osaka University)	Operating
NUCTE	Japan (Nihon University)	Operating

[a] Listed approximately by decreasing order of size; similarly sized devices at the same institution are listed together.

SOURCE: Office of Technology Assessment, 1987; from information supplied by the Los Alamos National Laboratory.

Figure 4-6.—Magnetic Mirrors



SOURCE: Lawrence Livermore National Laboratory, "Evolution of the Tandem Mirror," *Energy and Technology Review*, November 1986.

ing. While particle losses from the end cells are high, these losses can be compensated by injecting new particles.

The tandem mirror concept was developed simultaneously in the United States and the Soviet Union in the late 1970s. The Mirror Fusion Test Facility B (MFTF-B), located at Lawrence Livermore National Laboratory in California, is the largest mirror device in the world and the largest non-tokamak magnetic confinement fusion experiment. Budget cuts, however, forced MFTF-B to be mothballed before it could be used experimentally. The Tandem Mirror Experiment Upgrade (TMX-U) at Livermore, a smaller version of MFTF-B, was terminated as well, and the TARA device at the Massachusetts Institute of Technology will be shut down in 1988. At that point, Phaedrus at the University of Wisconsin will be the only operational U.S. mirror machine. Mirror research is still conducted in the Soviet Union and Japan. Table 4-7 presents a list of major world tandem mirror facilities.

Dense Z-Pinch

In this concept, a fiber of frozen deuterium-tritium fuel is suddenly vaporized and turned into plasma by passing a strong electric current through it. This current heats the plasma while simultaneously generating a strong magnetic field encircling the plasma column (figure 4-7), "pinching" it long enough for fusion reactions to occur. Many devices investigated in the earliest days of fusion research in the 1950s operated in a similar manner, but they were abandoned because their plasmas had severe instabilities and were unable to approach the confinement times needed to generate fusion power.

The dense z-pinch differs from the 1950s pinches in several important aspects that, as calculations and experiments have shown, improve stability. Crucial to the modern experiments are precisely controlled, highly capable power supplies that would have been impossible to build with 1950s technology, and the use of solid, rather than gase-

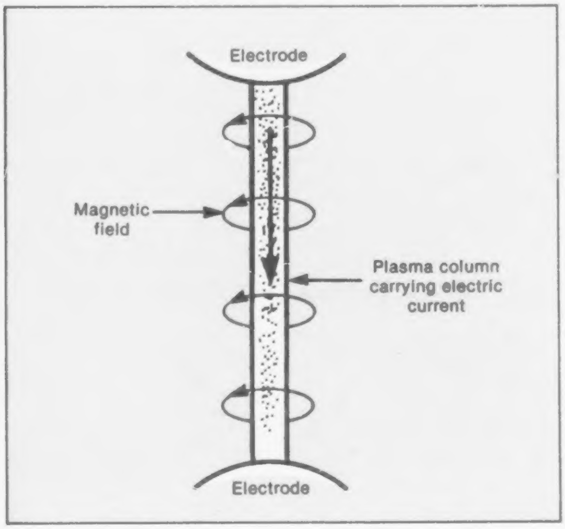
Table 4-7.—Major World Tandem Mirrors[a]

Device	Location	Status
MFTF-B	United States (LLNL)	Mothballed
TMX-U	United States (LLNL)	Mothballed
Gamma-10	Japan (Tsukuba University)	Operating
TARA	United States (MIT)	To be terminated, fiscal year 1988
Phaedrus	United States (University of Wisconsin)	Operating
Ambal M	USSR (Novosibirsk)	Under construction

[a] Listed in decreasing order of size

SOURCE: Office of Technology Assessment, 1987, from data supplied by the Lawrence Livermore National Laboratory.

Figure 4-7.—Dense Z-Pinch



SOURCE: Office of Technology Assessment, 1987

ous, fuel to initiate the discharge. However, it is much too early to tell whether this concept can be developed successfully. If the concept can be developed, the device has the potential to be far smaller and far less expensive than devices based on other concepts. External magnets are not needed since the plasma current supplies the entire confining field. Dense z-pinch research is taking place in the United States at two facilities: the Naval Research Laboratory and Los Alamos National Laboratory.

Conclusions Concerning Confinement Approaches

A number of general conclusions can be drawn from studies of the confinement concepts that have evolved over the past 10 to 15 years:

- **Many fusion concepts are under study because the frontrunner tokamak, while likely to be scientifically feasible, may yet be found weak in some critical area or less economically attractive than alternatives.** Features being studied in alternate concepts include eased conditions for steady-state operation, reduced external magnet complexity and cost, and improved use of the magnetic field. Searching for optimum reactor configurations and developing further understanding of the fusion process mandate that the range of concepts under investigation not be prematurely narrowed.

  The tokamak concept is by far the most developed, and it has attained plasma conditions closest to those needed in a fusion reactor. At present and for the next several years, studies of reactor-like plasmas will be done with tokamaks because no other concept has yet proven that it can reach reactor conditions. A number of other confinement concepts have features that might make them preferable to the tokamak if they are capable of progressing to an equivalent stage of performance. It remains to be seen which of these concepts will attain that performance level, what their development will cost, and to what degree the tokamak concept itself will further improve.
- **Different confinement studies complement each other.** Knowledge obtained through research on a specific concept often can be generalized. Throughout the history of fusion research, plasma science issues originally investigated because of their relevance to a particular concept have become important to studies of other concepts as well.
- **A great deal of progress in understanding fusion plasmas and confinement concepts has been made to date.** Many concepts

studied earlier, such as the simple magnetic mirror, are no longer studied today because they cannot compare attractively to improved or alternate concepts. At the same time, as in the case of the dense z-pinch, problems once considered intractable may be solved with additional scientific understanding and more advanced technology.

- **Research on all confinement concepts has benefited from international cooperation.** Studies undertaken by different groups in different countries enhance each other significantly. Furthermore, advances by one program have frequently stimulated additional progress in other programs. International cooperation in fusion research is discussed further in chapter 7.
- **Not all confinement concepts can be developed to reactor scale.** Promising concepts require study at greater levels of capability before their potential as reactor candidates can be assessed. Moreover, since this has largely been an empirical program, advanced studies will require larger and increasingly more expensive facilities. Fiscal constraints will almost certainly require that not all of the concepts be "promoted" to subsequent stages of development. Criteria such as development cost, characteristics of the end product, and likelihood of success must be developed for selecting which concepts are to be pursued further.
- **Progress in fusion science depends on progress in fusion technology.** Time after time, the exploration of new ranges of plasma behavior has been made possible by the development of new heating, fueling, and plasma shaping technologies.

SCIENTIFIC PROGRESS AND REACTOR DESIGN

Different Dimensions of Progress

To form the basis of a viable fusion reactor, a confinement concept must meet two objectives. First, it must satisfy scientific performance requirements—temperature, density, and confinement time—necessary for a plasma to produce fusion power. Progress towards those requirements is easy to measure.

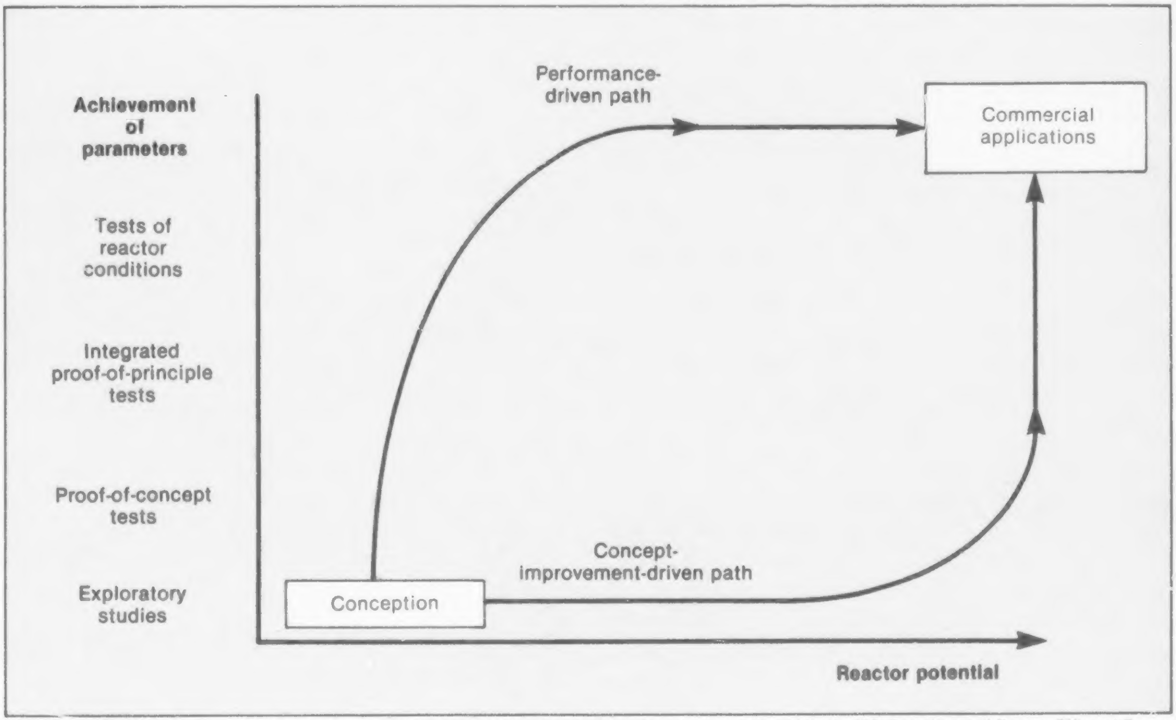
Second, a confinement concept must demonstrate "reactor potential." Unlike scientific performance, reactor potential is difficult to measure. A viable reactor must be built, operated, and maintained reliably, and it must be economically, environmentally, and socially acceptable. While fusion's acceptability in these respects depends on factors external to fusion technology, it also depends on the choice of confinement concept.

Each concept may have different advantages, and, in the absence of quantitative measures, the process of identifying the concepts that offer the most attractive reactors depends in large part on the innovation and technological optimism of the reactor designer. Also, attributes of an attractive reactor can be identified today, but the relative importance of these attributes may change as our understanding of fusion technology and future societal needs improves.

No matter how it is evaluated, reactor potential is a requirement that, along with scientific performance, must be satisfied by at least one confinement concept before fusion power can be realized. Figure 4-8 shows two different paths by which a concept can develop toward commercial use. Along the "performance-driven" path, a concept first demonstrates the ability to attain plasma parameters near those required to produce fusion power; subsequently, innovations or successive refinements show that the concept's scientific capabilities can be used in a viable reactor design. Alternatively, along the "concept-improvement-driven" path, features that are attractive in a fusion reactor—e.g., compact size, ease of maintenance, simple construction, and reliable operation—are apparent before the scientific performance necessary to produce fusion power is demonstrated.

The actual development of any given confinement concept will fall somewhere between these extremes. Development of the tokamak appears to be closer to the performance-driven curve. Its scientific performance, along with its use in de-

Figure 4-8.—Alternate Paths for Concept Development


Achievement of parameters
Tests of reactor conditions
Integrated proof-of-principle tests
Proof-of-concept tests
Exploratory studies
Performance-driven path
Commercial applications
Concept-improvement-driven path
Conception
Reactor potential

SOURCE: Adapted from Argonne National Laboratory, *Technical Planning Activity: Final Report*, commissioned by the U.S. Department of Energy, Office of Energy Research, ANL/FPP-87-1, January 1987, figure 1.5, p. 56.

veloping plasma technology and diagnostics, has been the primary motivation for study to date; improvements to the basic tokamak concept are currently focused on improving reactor potential. Other concepts are more concept-improvement-driven in that their features might make them preferable to the tokamak if they can reach reactor scale. However, the ability of other concepts to attain the necessary plasma conditions is much less certain because their experimental databases are less developed.

Scientific Progress

Energy Gain

An important measure of scientific progress towards attaining reactor-relevant conditions is *energy gain*, denoted as "Q." Energy gain is the ratio of the fusion power output that a device generates to the input power injected into the plasma. Input and output power are measured at some instant after the plasma has reached its operating density and temperature. In experimental plasmas that do not contain tritium and therefore do not produce significant amounts of fusion power, an "equivalent Q" is measured. It is defined as the Q that would be produced by the plasma if it were fueled equally by both deuterium and tritium (D-T) and if it had attained the same plasma parameters.[2]

The numerator of the Q ratio includes all the fusion power produced by the plasma, even though most of the output power (80 percent) immediately escapes from the plasma via energetic neutrons. The denominator of the ratio—the power used to heat the plasma—greatly underestimates the amount of power actually consumed. Losses incurred in generating heating power and delivering it to the plasma are not included, nor is the power needed for the confining magnets, vacuum system, and other support systems. **In present-generation experiments, the power excluded from the definition of Q is as much as 35 times greater than the power accounted for in this ratio.**[3]

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[2] "Equivalent Q" is either calculated from the measured plasma density and temperature or derived from actual measurements of deuterium-deuterium (D-D) fusion reactions. Since the ratio between the D-T reaction rate and the D-D reaction rate under the same conditions is believed known, a measurement of D-D reactions can be used to infer what the D-T fusion yield would be under the same conditions.

Q excludes most of the power drawn by a fusion experiment because it is a scientific measure that is not intended to gauge engineering progress. Present experiments, needing only to operate for short pulses, have not been designed to minimize consumed power; to lessen construction cost, they use magnets that are far less efficient than those likely to be used in future reactors. Similarly, the inefficiencies in generating the externally applied plasma heating power are not included because auxiliary heat is not required once a plasma generates enough fusion power to become self-sustaining. Even so, some external power will be required in any steady-state plasma device except the stellarator to maintain electrical currents within the plasma.

Figure 4-9 shows the plasma temperatures and confinement parameters needed to obtain Qs of at least 1, a condition known as "breakeven." The plasma temperatures and confinement parameters that have been attained experimentally by various confinement configurations are also shown. No device has yet reached breakeven, although tokamak experiments have clearly come the closest.

Ignition

The most significant region in figure 4-9 is *ignition* in the top right corner. An ignited D-T plasma not only generates net fusion power but also retains enough heat to continue producing fusion reactions without external heat. The Q of an ignited plasma is infinite, since the plasma generates output power without auxiliary input power from external sources. (Power to drive currents in the plasma and to cool the magnets to their operating temperature will be required even for ignited plasmas, but, as stated above, this power is not included in Q.)

Successfully reaching ignition—or at least successfully generating a plasma that produces many times more power than is input into it—will be a major milestone in determining fusion's technological feasibility. The energy and the reaction products generated in a plasma producing appreciable amounts of fusion power will significantly affect the plasma's behavior. Understanding these effects may be crucial to utilizing self-sustaining fusion reactions in reactors, and these effects cannot be studied under breakeven conditions alone.

Breakeven

The breakeven curve in figure 4-9 shows the conditions under which a plasma generates as much power through fusion reactions as is injected into it to maintain the reactions. Although reaching breakeven will be a major accomplishment, it will not have the technical significance of reaching ignition. Due to the way that energy gain is defined, the breakeven threshold in some respects is arbitrary, and it depends significantly on the manner in which the plasma is heated. Crossing the threshold does not cause a significant change in plasma behavior and in no way indicates that the experiment is able to power itself. Problems that are not fully evident under breakeven conditions may yet be encountered on the way to ignition.

The breakeven curve in figure 4-9 is calculated for plasmas that are uniformly heated. If the plasma is heated in such a way that a small fraction of the plasma particles become much hotter than the rest, this fraction will produce a disproportionate amount of fusion power and the breakeven requirements can be substantially lowered. For this reason, plasmas heated with neutral beams can reach breakeven under conditions that would not be sufficient without the use of neutral beams.

Neutral beams are extremely hot jets of neutral atoms that can penetrate the confining mag-

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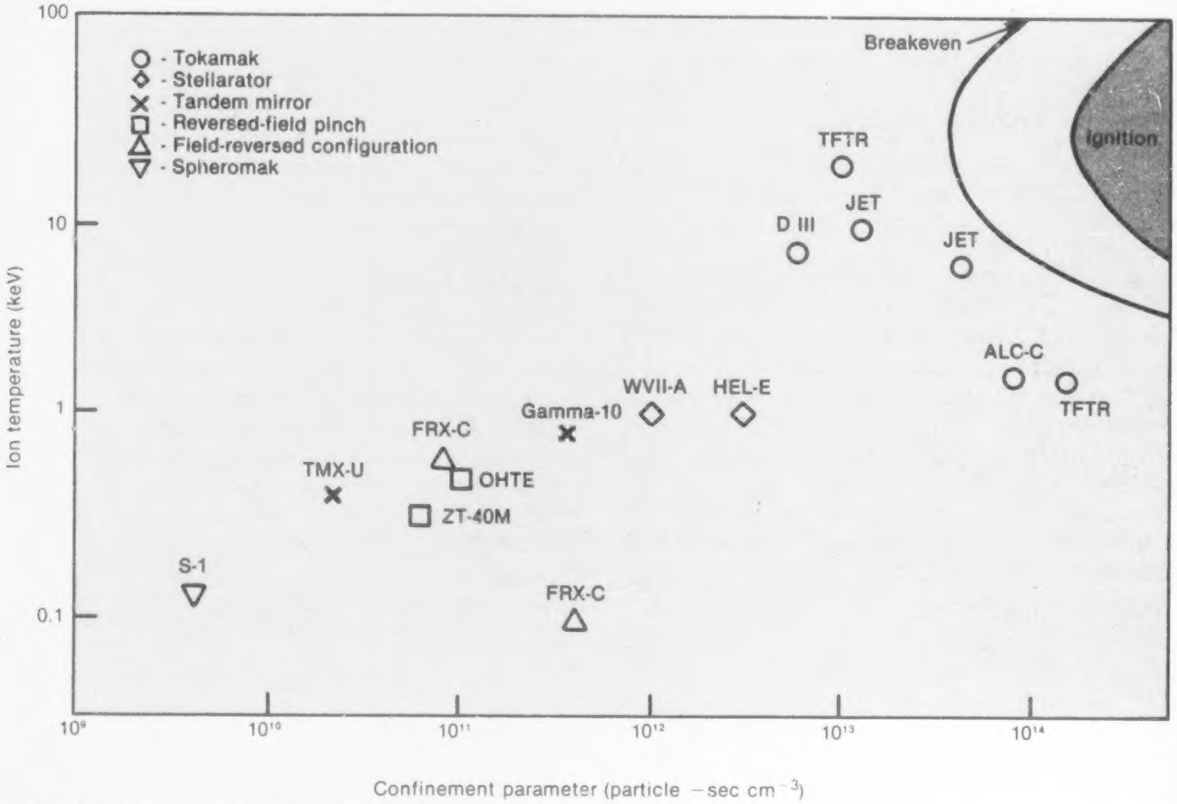
[3] See specifications for the Tokamak Fusion Test Reactor at the Princeton Plasma Physics Laboratory, footnote 4 below.

Figure 4-9.—Plasma Parameters Achieved by Various Confinement Concepts



KEY: S-1: Spheromak-1; Princeton Plasma Physics Laboratory, Princeton, NJ.
TMX-U: Tandem Mirror Experiment Upgrade; Lawrence Livermore National Laboratory, Livermore, CA.
ZT-40M: Toroidal Z-pinch, -40, Modified; Los Alamos National Laboratory, Los Alamos, NM.
FRX-C: Field-Reversed Experiment C; Los Alamos National Laboratory, Los Alamos, NM.
OHTE: Ohmically Heated Toroidal Experiment; GA Technologies, Inc., San Diego, CA.
Gamma-10: University of Tsukuba, Ibaraki, Japan.
WVII-A: Wendelstein VII-A; Institute for Plasma Physics, Garching, Federal Republic of Germany.
HEL-E: Heliotron-E; Kyoto University, Kyoto, Japan.
D III: Doublet III; GA Technologies, Inc., San Diego, CA.
JET: Joint European Torus; JET Joint Undertaking, Abingdon, United Kingdom.
TFTR: Tokamak Fusion Test Reactor; Princeton Plasma Physics Laboratory, Princeton, NJ.
ALC-C: Alcator C; Massachusetts Institute of Technology, Cambridge, MA.

SOURCE: Office of Technology Assessment, 1987.

netic fields to enter the plasma. Beam atoms collide with particles inside the plasma and become electrically charged, thereby becoming trapped by the magnetic field. Through collisions, much of the energy carried by the beams is transferred to the "target" plasma, heating it up. In the process, the beam particles themselves cool down.

However, it will take many collisions for the beam particles to cool down to the temperature of the target plasma. As long as the beams are on, the most recently injected beam particles are significantly hotter than the original plasma particles. (Once the beams are turned off, the injected particles cool down to the temperature of the remaining plasma.) Since the fusion reaction rate increases very rapidly with temperature, the hotter particles from the neutral beam have a much higher probability of generating fusion reactions than other particles in the plasma. In this manner, a beam-heated plasma can achieve breakeven with plasma parameters up to a factor of 10 lower than those needed for plasmas heated by other mechanisms. However, since the beams themselves require so much power to operate, it is not expected that beam-heated plasmas will be used in reactors. Therefore, the lower breakeven threshold for beam-heated plasmas may not translate into lower requirements for a practical reactor.

The Tokamak Fusion Test Reactor (TFTR) at Princeton Plasma Physics Laboratory was designed to take advantage of beam heating. It is expected that breakeven-equivalent (breakeven conditions in a plasma not containing tritium) will be obtained sometime between fall 1987 and spring 1988. Experiments to realize true breakeven using tritium are scheduled for the end of 1990. These achievements will be important because, for the first time, a significant amount of heat from fusion power will be produced in a magnetic fusion device. Moreover, successful D-T operation of TFTR will provide important tritium-handling experience necessary for future reactor operation.

Nevertheless, TFTR—not being an engineering facility—does not address most of the technological issues that must be resolved before a fusion reactor can be built. Moreover, it will not reach ignition, and the advantage it derives from using neutral beams will probably not translate into a workable reactor. It does not incorporate advanced physics aspects that have been identified since its design in the 1970s. TFTR will not—and never was intended to—have the capability to generate electricity from the fusion power it will produce. **Even on attaining breakeven, the TFTR experiment as a whole—as opposed to the TFTR plasma alone—will produce less than 3 percent of the power it will consume.**[4]

State of the Art

Temperature and Confinement.—Figure 4-9 shows results that have been attained by each of the confinement concepts to date. Tokamak experiments have clearly made the most progress in terms of coming the closest to the ignition region.

TFTR, in particular, has reached the highest temperature and confinement parameters of any magnetic fusion experiment. In 1986, TFTR attained ion temperatures of 20 kiloelectron volts (keV) or more than 200 million degrees C, well over the temperature needed for breakeven or ignition. However, these high-temperature results were obtained in a relatively low-density plasma having a confinement parameter of 10^{13} second-particles per cubic centimeter, which is about half of the confinement parameter needed to reach breakeven at that temperature. The equivalent Q actually attained by the plasma was 0.23. Use of neutral beam heating under these conditions reduces the breakeven threshold by almost a factor of four; a plasma heated to 20 keV without the use of neutral beams would need a confinement parameter 7.5 times higher than was attained to reach equivalent breakeven.

In a separate experiment at a lower temperature of 1.5 keV, TFTR reached a confinement parameter of 1.5×10^{14} second-particles per cubic centimeter. Had this confinement been attained at a temperature of 20 keV, TFTR would have been well above equivalent breakeven, coming close to meeting the equivalent ignition condition. However, in practice, TFTR will not be able to attain temperature and confinement values this high simultaneously. Temperature can be raised at the expense of confinement, and vice versa, but the product of the two—which determines equivalent Q—is difficult to increase. With additional neutral beam power and other improvements, TFTR may well be able to raise its equivalent Q from 0.23 to 1 and reach equivalent breakeven. However, it is extremely unlikely that equivalent Qs much greater than 1 are attainable in TFTR.

Beta.—The beta parameter, also called the "magnetic field utilization factor," measures the efficiency with which the energy of the magnetic field is used to confine the energy of the plasma. Beta is defined as the ratio of the plasma pres-

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[4] TFTR is being upgraded to deliver up to 27 megawatts of neutral beam power to the plasma. To reach breakeven, where the fusion power generated equals the external power injected into the plasma, 27 megawatts of fusion power would have to be generated in the plasma. If reaching breakeven were to require TFTR to draw near the maximum amount of power available from its electrical supply, it could consume close to 1,000 megawatts of electricity. This amount is 37 times greater than the fusion power to be produced at breakeven.

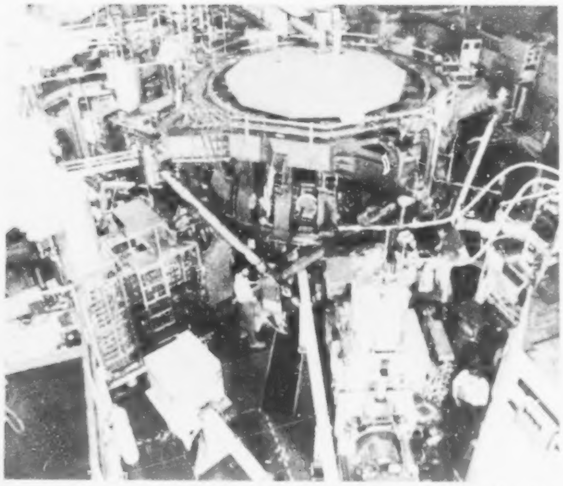

Photo credit: Princeton Plasma Physics Laboratory

The PBX tokamak at Princeton Plasma Physics Laboratory.

sure to the magnetic field pressure.[5] Record tokamak values for beta of 5 percent, in the PBX experiment at Princeton Plasma Physics Laboratory, and 6 percent, in the D III-D experiment at GA Technologies, have been attained. These results are especially important in that they generally validate theoretical models that predict how further improvements in beta can be obtained.

In a fusion reactor, the fusion power output per unit volume of the plasma would be proportional to beta squared times the magnetic field strength to the fourth power. Since tokamaks have relatively low betas compared to many of the other confinement concepts currently studied, improving the beta of tokamaks can be useful. Betas greater than 8 percent are indicated in some system studies as being necessary for economical performance,[6] and values considerably exceeding that have been obtained by certain other confinement concepts (albeit to date at much poorer temperatures and confinement parameters). However, physical phenomena in the plasma prevent beta values from being increased indefinitely. These phenomena, which differ from concept to concept, are not completely understood; gaining additional understanding in this area is a high priority.

Low beta values can also be compensated by raising the magnetic field strength. Whereas raising beta primarily involves plasma physics issues, the issues involved in raising the magnetic field strength are primarily engineering-related: stronger magnetic fields are more difficult and expensive to generate and place greater stress on the magnet structures. At some field strength, the advantages of stronger magnetic fields will be outweighed by the additional expense of the magnets.

Scaling.—Understanding how tokamak performance can be expected to improve is crucial to evaluating the tokamak's potential for future reactors as well as to designing next-generation tokamak experiments. As mentioned earlier, the complete theoretical mechanism determining tokamak scaling has yet to be understood. Observationally, plasma confinement has been found to improve with increased plasma size. Empirical data also show that tokamak confinement improves when plasma density is increased, but that this behavior holds only for ohmically heated plasmas. Non-ohmically heated plasmas follow what has come to be known as "L (Low)-mode" scaling, in which confinement degrades as increasing amounts of external power are injected.

A few years ago, experiments on the German Axisymmetric Divertor Experiment (ASDEX) discovered a mode of tokamak behavior described by a more favorable scaling, labeled "H (High)-mode." In this mode, performance even with auxiliary heating behaved more like the original, ohmically heated plasmas. However, H-mode scaling could be achieved only with a particular combination of device hardware and operating conditions. Subsequently, additional work at other tokamaks has broadened the range of conditions under which this more favorable behavior can be found. The challenge to tokamak researchers is to obtain H-mode scaling in configurations and operating regimes that are also con-

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[5] Plasma pressure is equal to plasma temperature times density and is proportional to the plasma energy per unit volume; magnetic field pressure, which is proportional to the square of the magnetic field strength, is a measure of the energy stored in the magnetic field per unit volume.

Typical reactor studies indicate that the plasma in an operating fusion reactor will have a pressure several times that of the earth's atmosphere at sea level. The plasma density, however, will only be about 1/100,000 the density of the atmosphere at sea level. That so few particles can exert such a high pressure is a measure of their extreme temperature: about 10,000 electron volts, or more than 100 million degrees C.

[6] For example, J. Sheffield, et al., *Cost Assessment of a Generic Magnetic Fusion Reactor*, Oak Ridge National Laboratory, ORNL/TM-9311, March 1986, p. 5.

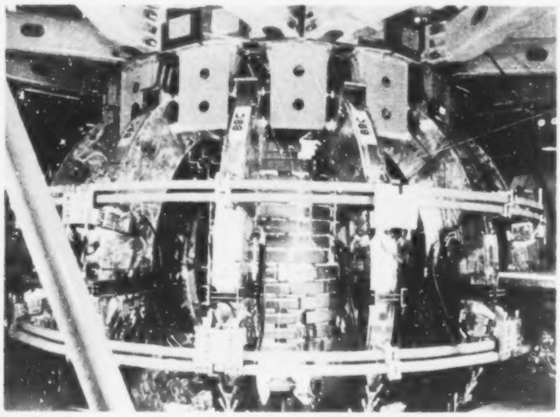


Photo credit: Commission of the European Communities

The ASDEX tokamak at the Max-Planck Institute for Plasma Physics, Garching, Federal Republic of Germany.

ducive to attaining reactor-like temperatures and densities.

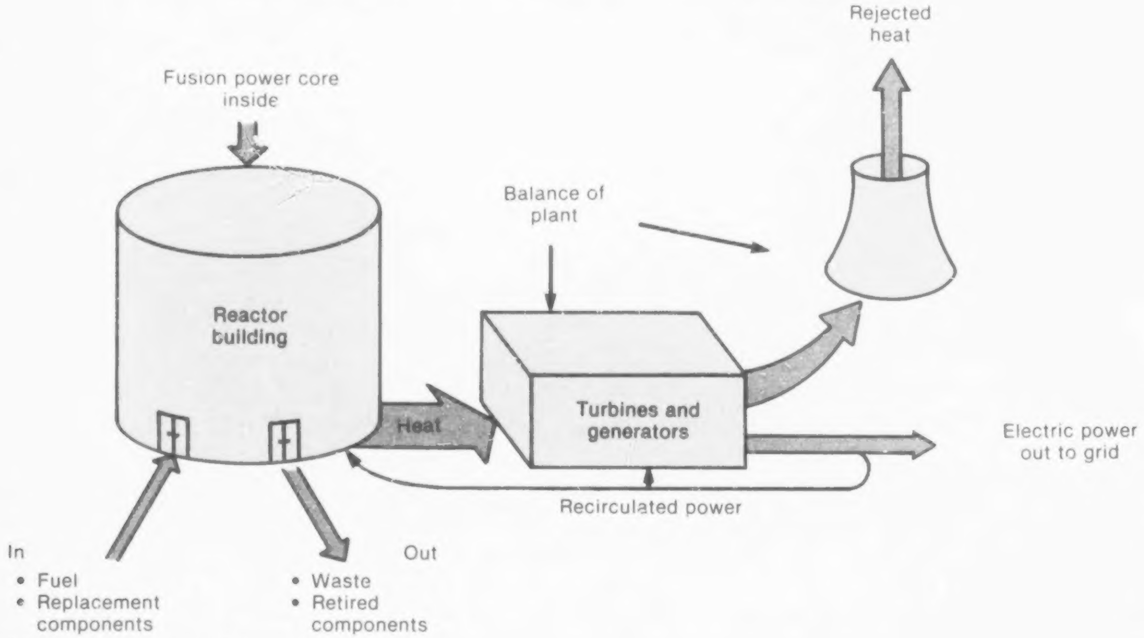
Reactor Design

Just as an automobile is much more than spark plugs and cylinders, a fusion reactor will contain many systems besides those that heat and confine the plasma. Fusion's overall engineering feasibility will depend on supporting the fusion reaction, converting the power released into a more usable form of energy, and ensuring operation in a safe and environmentally acceptable manner. **Developing and building these associated systems and integrating them into a functional whole will require a technological development effort at least as impressive as the scientific challenge of creating and understanding fusion plasmas.**

The following section describes the systems in a fusion reactor. Since the tokamak confinement concept and the D-T reaction are the most extensively studied, a tokamak-based reactor fueled with D-T is used as an example. However, most of the systems described here would be found, in some form, in reactors based on other concepts as well.

The overall fusion generating station (figure 4-10) consists of a *fusion power core*, containing the systems that support and recover energy from the fusion reaction, and the *balance of plant* that converts this energy to electricity using equip-

Figure 4-10.—Systems in a Fusion Electric Generating Station


Rejected heat
Fusion power core inside
Balance of plant
Reactor building
Heat
Turbines and generators
Electric power out to grid
Recirculated power
In
• Fuel
• Replacement components
Out
• Waste
• Retired components

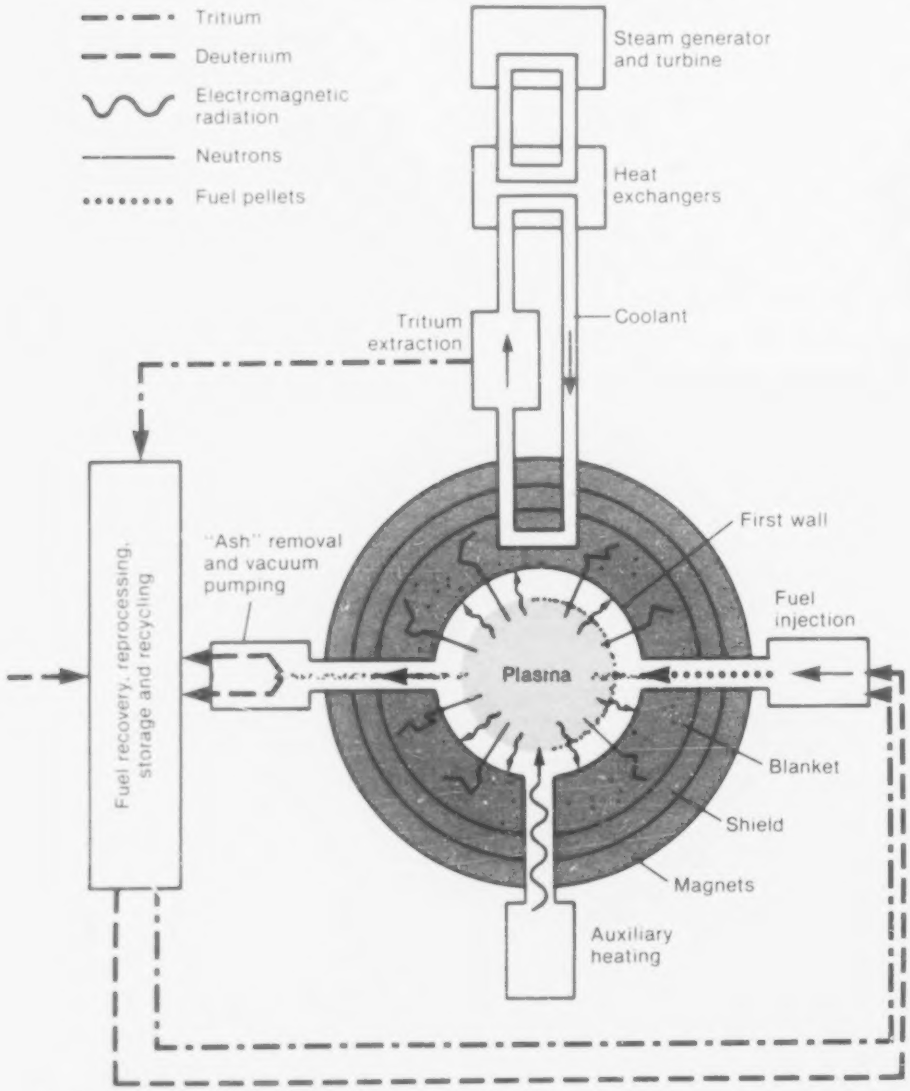
SOURCE: Office of Technology Assessment, 1987

ment similar to that found in present electricity generating stations. Features that might convert fusion power to electricity more directly in advanced fusion reactors are described in a subsequent section.

Fusion Power Core

The fusion power core, shown schematically in figure 4-11, is the heart of a fusion generating station. It consists of the plasma chamber, the surrounding blanket and first wall systems that recover the fusion energy and breed tritium fuel, the magnet coils generating the necessary magnetic fields, shields for the magnets, and the fueling, heating, and impurity control systems. Before an acceptable design for a fusion power core can be developed, the behavior of fusion plasmas must be understood under all conditions that might be encountered. Furthermore, significant

Figure 4-11.—Systems in the Fusion Power Core


Tritium
Deuterium
Electromagnetic radiation
Neutrons
Fuel pellets
Steam generator and turbine
Heat exchangers
Coolant
Tritium extraction
Fuel recovery, reprocessing, storage and recycling
"Ash" removal and vacuum pumping
First wall
Fuel injection
Plasma
Blanket
Shield
Magnets
Auxiliary heating

SOURCE: Modified from "The Engineering of Magnetic Fusion Reactors," by Robert W. Conn. Copyright 1983 by Scientific American, Inc. All rights reserved.

advances must be made in *plasma technologies*, which confine and maintain the plasma, and *nuclear technologies*, which recover heat from the plasma, breed fuel, and ensure safe operation.

Balance of Plant

Balance of plant generally describes the systems of a fusion generating station outside of the fusion power core. In the example shown in figure 4-11, the balance-of-plant resembles systems found in other types of electric generating stations. These systems use heat provided by the fusion core to produce steam that drives turbines and generates electricity. The steam is cooled by passing through the turbines, and the remaining heat in the steam is exhausted through cooling towers or similar mechanisms.

More advanced systems that convert plasma energy directly into electricity also may be possible. Fusion reactors incorporating such systems could be made more efficient than those using steam generators and turbines.

FUSION POWER CORE SYSTEMS

The Fusion Plasma

At the center of a fusion reactor, literally and figuratively, is the fusion plasma. A number of supporting technology systems create and maintain the plasma conditions required for fusion reactions to occur. These technologies confine the plasma, heat and fuel it, remove wastes and impurities, and, in some cases, drive electric currents within the plasma. They also recover heat, breed fuel, and provide shielding.

Further development of many of these plasma technologies is required before they will be capable of producing a reactor-scale plasma. Furthermore, each of these supporting systems affects plasma behavior, and the interactions are incompletely understood. Progress in both plasma technology and plasma science is therefore needed before reactor-scale fusion plasmas can be created.

Heating

Description.—Some heat loss from a plasma is inevitable (see box 4-A), but, with good confinement, the losses can be made up by external heating and/or by fusion self-heating. Different mechanisms for heating the plasma, illustrated in figure 4-12, are listed below.

Ohmic Heating.—Like an electric heater, a plasma will heat up when an electrical current is passed through it. However, the hotter a plasma gets, the better it conducts electricity and therefore the harder it is to heat further. As a result, ohmic heating is not sufficient to reach ignition in many configurations.

Neutral Beam Heating.—Energetic charged or neutral particles can be used to heat fusion plasmas. However, the same magnetic fields that prevent the plasma from escaping also prevent charged particles on the outside from easily getting in. Therefore, beams of energetic neutral (uncharged) particles that can cross the field lines are usually preferred for heating the plasma.

Radiofrequency Heating.—Electromagnetic radiation at specific frequencies can heat a plasma like a microwave oven heats food. Radiofrequency or microwave power beamed into a plasma at the proper frequency is absorbed by particles in the plasma. These particles transfer energy to the rest of the plasma through collisions.

Compression Heating.—Increasing the confining magnetic fields can heat a plasma by compressing it. This technique has been used in tokamak devices and is one reason for studying the field-reversed configuration confinement approach. As stated earlier, there is hope that compression may be sufficient to heat an FRC plasma to ignition.

Fusion Self-Heating.—The products of a D-T fusion reaction are a helium nucleus—an alpha particle—and a neutron. The neutron, carrying most of the reaction energy, is electrically uncharged and escapes from the plasma without reacting further. The alpha particle, carrying the rest of the energy from the fusion reaction, is charged and remains trapped within the confining mag-

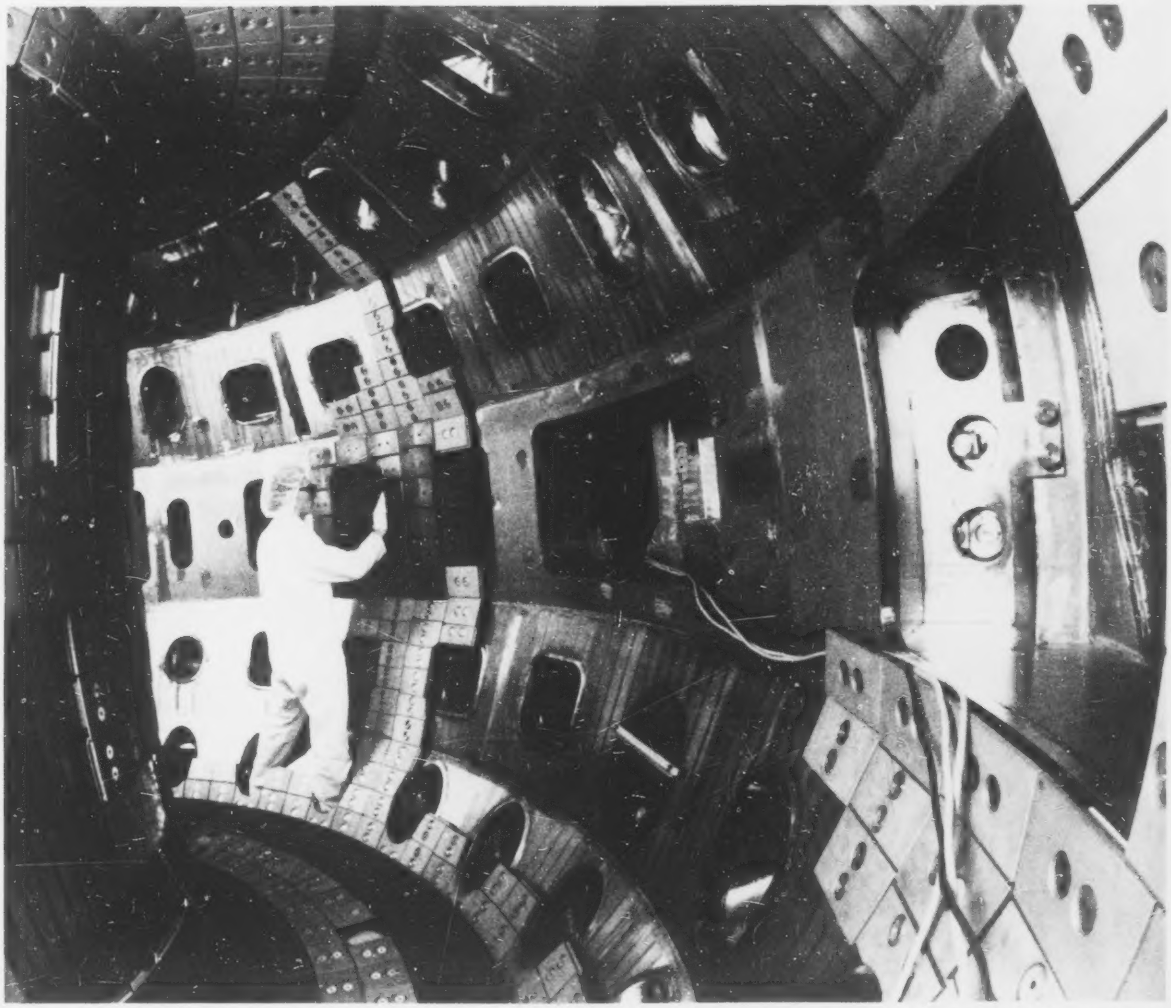


Photo credit: GA Technologies, Inc

View inside vacuum vessel of the D III-D tokamak at GA Technologies, San Diego, California. The plasma is contained within this vessel.

netic fields. Hundreds of times hotter than the surrounding plasma, the alpha particle heats other plasma particles through collisions.

Status.—Recent system studies show that radiofrequency (RF) heating offers significant advantages over neutral beam heating. Consequently, the U.S. neutral beam research program has been reduced while the RF heating program has grown. Various types of RF heating, using different frequencies of radiation from tens of megahertz (millions of cycles per second) to over a hundred gigahertz (billions of cycles per second), are under study. Each frequency range involves different technologies for generation and transmission.

Issues.—Additional research and development (R&D) in heating technologies is essential to meet the needs of future experiments and reactors. Key technical issues in RF heating are the development of sufficiently powerful sources of radiofrequency power (tens of megawatts), particularly at higher frequencies, and the development of launchers or antennas to transmit this power into

Box 4-A.—Plasma Energy Loss Mechanisms

Fusion experiments to date have encountered four different types of energy loss mechanisms in attempting to reach reactor-like plasma temperatures and confinement parameters. Some energy loss is inherent in any plasma and must be tolerated; other energy losses can be minimized and possibly eliminated if sufficiently understood.

1. **Particle Collisions.** If particles in a magnetically confined plasma never collided, they would spiral around magnetic field lines and would not be able to move across the field. In reality, collisions are rare but inevitable; a typical particle in a fusion-grade plasma device may travel thousands of times around the device before colliding with another particle. When particles on different field lines collide, they may jump to new field lines and in this manner can diffuse across the field to the edge of the plasma and out of the system.

   When particles diffuse out of the plasma, they carry energy with them. Such losses place an upper limit, termed "classical confinement," on the length of time that the energy in a plasma can be confined. Increasing the size of the plasma increases the maximum confinement time. As fusion experiments approach reactor scale and performance, they generally get larger.
2. **Radiative Cooling.** Various processes cause energy to be lost from the plasma in the form of X-rays, ultraviolet light, and other electromagnetic radiation. The most severe radiative losses are due to impurities in the plasma. As a result, it is important to keep reactor-grade plasmas pure. (In addition to increasing heat loss, impurities are also undesirable in fusion plasmas because they dilute the fuel.)
3. **Fine-Scale Plasma Instabilities.** Turbulence and other instabilities occurring over distances comparable with the orbits of individual particles about their magnetic field lines can result in much more rapid energy losses than those due to "classical" diffusion across the field lines. Such disturbances are often termed "anomalous transport" or "microinstabilities."
4. **Large-Scale Plasma Instabilities.** Deformations of the confining magnetic field due to spontaneous rearrangements of the plasma and field can lead to an increased loss of plasma. The most extreme of these instabilities is the disruption, observed in plasmas carrying electric currents, in which the entire magnetic structure "unravels" and the plasma escapes rapidly to the wall of the chamber.

the plasma, particularly at lower frequencies. Resolution of these issues will require technological development as well as improved understanding of the interaction between radio waves and plasmas.

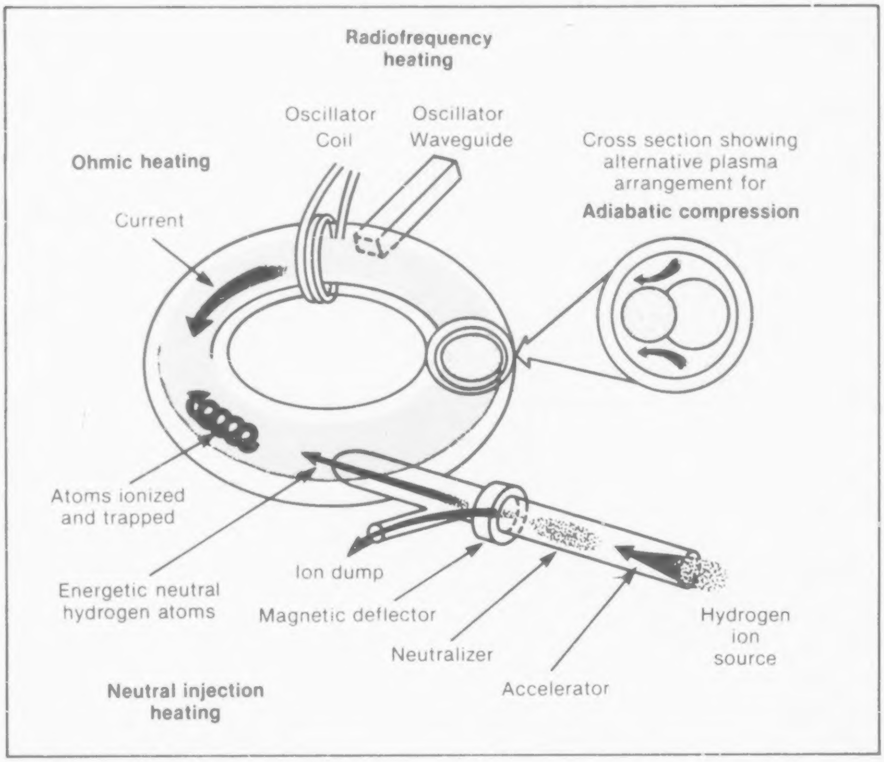
Since no ignited plasma has yet been produced, the effects of fusion self-heating on plasma confinement and other plasma properties are not experimentally known. Confinement could degrade, just as it does with other forms of auxiliary heating. Although self-heating can be simulated in some ways in non-ignited plasmas, its effects can be fully studied only upon reaching high energy gain or ignition. The ignition milestone, therefore, is crucial to the fusion program, and understanding the behavior of ignited plasmas is one of the program's highest scientific priorities.

Fueling

Description.—Any fusion reactor that operates in pulses exceeding a few seconds in length must be fueled to replace particles that escape the plasma and, to a lesser extent, those that are consumed by fusion reactions. Firing pellets of frozen deuterium and tritium into the plasma currently appears to be the best approach for fueling. Both pneumatic (compressed gas) and centrifugal (sling) injectors have been used (figure 4-13). Neutral beam fueling has been used in experiments, but fueling reactors in this way would take excessive amounts of power.

Status.—Pellets up to 4 millimeters in diameter have been fired into experimental plasmas at speeds of up to 2 kilometers per second and at

Figure 4-12.—Plasma Heating Mechanisms


Radiofrequency heating
Oscillator Coil
Oscillator Waveguide
Ohmic heating
Current
Cross section showing alternative plasma arrangement for
Adiabatic compression
Atoms ionized and trapped
Energetic neutral hydrogen atoms
Ion dump
Magnetic deflector
Neutralizer
Accelerator
Hydrogen ion source
Neutral injection heating

SOURCE: Oak Ridge National Laboratory

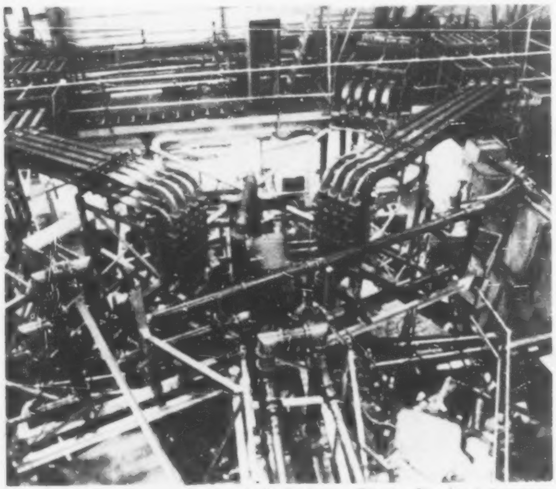


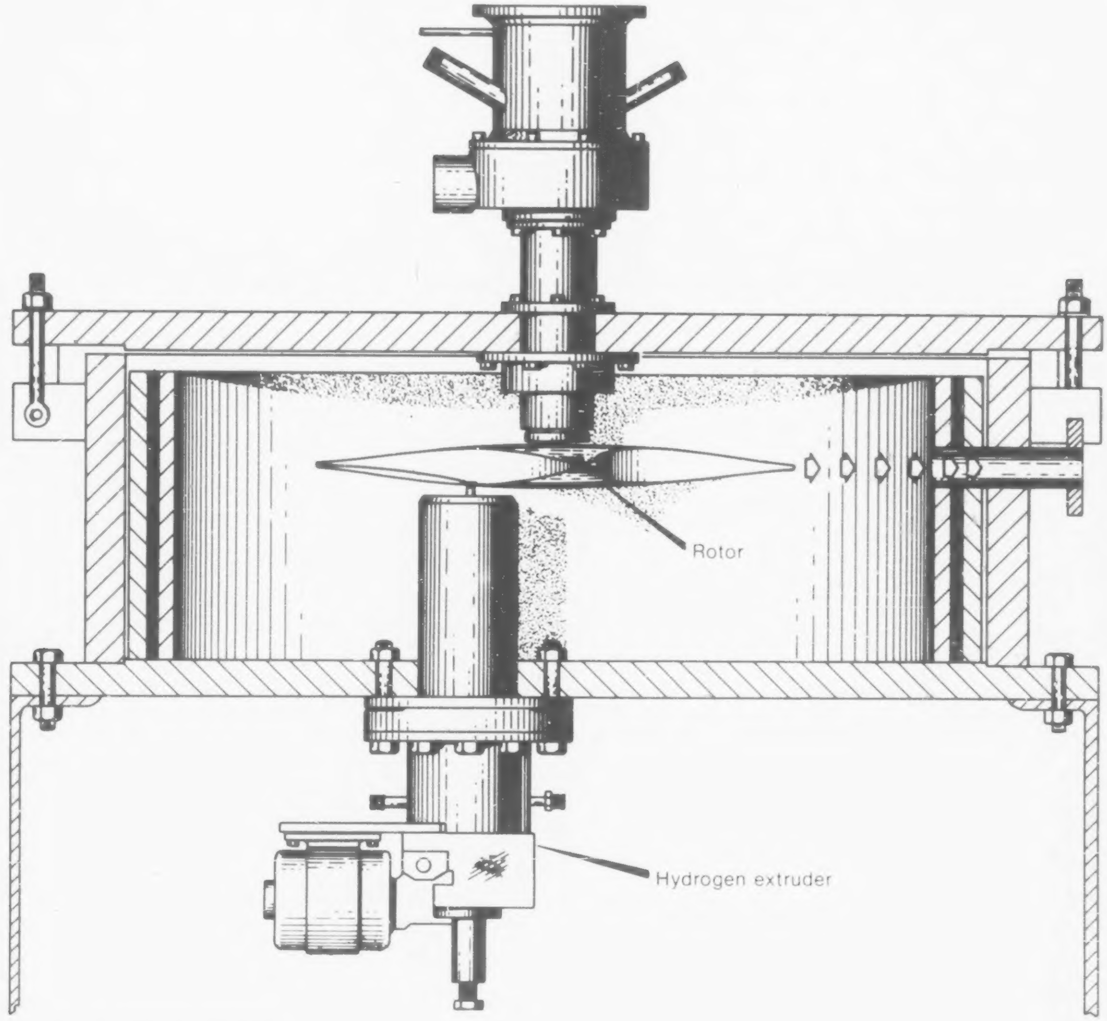
Photo credit: Princeton Plasma Physics Laboratory

Princeton Large Torus at PPPL, showing waveguides for the RF heating system.

repetition rates of 5 to 40 pellets per second. U.S. development of pellet fueling technology, centered at Oak Ridge National Laboratory, is well ahead of fueling technology development elsewhere in the world. By building state-of-the-art pellet injectors for use on foreign experiments, the United States is able in return to gain access to foreign experimental facilities.

Issues.—Reactor-scale plasmas will be denser, hotter, and perhaps bigger than the plasmas made to date in fusion experiments; moreover, reactor plasmas will contain energetic alpha particles. All these factors will make it much more difficult for pellets to penetrate reactor plasmas than plasmas made in present-day facilities. Penetration to the center of the plasma, most desirable from a theoretical point of view, probably will be extremely difficult in reactor plasmas. Experiments are now underway to understand how deeply a pellet

Figure 4-13.—Centrifugal Pellet Injection



SOURCE: Oak Ridge National Laboratory

must penetrate. Tokamaks, for example, appear to have a mechanism, not yet understood, that transports fuel to the center of the plasma. Fuel might be brought into the center more effectively in some of the alternate confinement concepts with turbulent plasmas, such as the reversed-field pinch or the spheromak.

If deeper penetration is required than can now be attained, either larger pellets or higher injection speeds will be needed. Larger pellets are not difficult to produce, but they may disturb the plasma too much; additional work needs to be done to determine how fuel pellets affect plasma behavior. If larger pellets cannot be used, higher injection speed will be required, which is technologically much more difficult. Improving present techniques is unlikely to increase injection speeds by more than about a factor of 2. New techniques capable of producing much higher injection speeds are being investigated, but the pellets themselves may not survive injection at these speeds due to fundamental limitations in their mechanical properties.[7]

Current Drive

Description.—Several confinement concepts, including the tokamak, require generation of an electric current inside the plasma. In most present experiments, this current is generated by a transformer. In a transformer, varying the electric current in one coil of wire generates a magnetic field that changes with time. This field passes through a nearby second coil of wire—or in this case the conducting plasma—and generates an electric current in that coil or plasma. Varying the magnetic field is essential; a constant magnetic field cannot generate current.

In tokamak experiments, a coil located in the "doughnut hole" in the center of the plasma chamber serves as one coil of the transformer. Passing a steadily increasing current through this coil creates an increasing magnetic field, which generates current in the plasma. When the current in the first coil levels off at its maximum value, its magnetic field becomes constant, and the current in the plasma peaks and then starts to decay. If the fusion plasma requires a plasma current, its pulse length is limited by the maximum magnetic field of the first coil and the length of time taken for the plasma current to decay.[8]

Status.—Techniques are now being studied for generating continuous plasma currents, rather than pulsed ones, because steady-state reactors are preferable to ones that operate in pulses.[9] Injecting radiofrequency power or neutral beams into the plasma might be able to generate such steady-state currents in tokamaks. The injected power or beams generate currents either by "pushing" directly on electrons in the plasma or by selectively heating particles traveling in one direction. Experiments have confirmed the theory of radiofrequency current drive and have succeeded in sustaining tokamak current pulses for several seconds.

Some other confinement concepts, such as the reversed-field pinch or the spheromak, can generate plasma currents with small, periodic variations in the external magnetic fields. Such current-drive technologies do not involve complex external systems.

Issues.—The principal issues involving steady-state current drive are cost and efficiency, especially under reactor conditions. In particular, the radiofrequency technique becomes less efficient as the plasma density increases. This inefficiency could pose problems because reactors will probably operate at higher densities to maximize generated power. **At this time, it is not known whether the efficiency of continuous current drive can be increased to the point where it could replace the pulsed transformers now used in tokamaks.** However, radiofrequency current drive might also be used to augment the pulsed transformer by starting up the plasma current in a period of low-density operation. Once the plasma current was started, the density could be raised and the transformer used to sustain the current. The radiofrequency current drive together with the transformer would be able to generate longer lasting pulses than the transformer alone.

Reaction Product and Impurity Control

Description.—Alpha particles, which build up as reaction products in steady-state or very long-pulse fusion reactors, will have to be removed so that they do not lessen the output power by diluting the fuel and increasing energy loss by radiation. Devices that collect ions at the plasma edge can be used to remove alpha particles from the plasma. Alpha particles, when combined with electrons that are also collected at the plasma edge, form helium gas that can be harmlessly released. Unburned fuel ions also will be collected; these will be converted to deuterium and tritium gas, which will have to be separated from the helium and reinjected into the plasma.

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[7] Argonne National Laboratory, Fusion Power Program, *Technical Planning Activity: Final Report*, commissioned by the U.S. Department of Energy, Office of Fusion Energy, ANL/FPP-87-1, January 1987, p. 189.

[8] In tokamaks, this decay time can be thousands of seconds. For confinement concepts with plasmas that are more resistive to electric currents, the decay time is shorter, on the order of hundreds of seconds. Operating for periods of time longer than the decay time requires non-transformer current drive mechanisms.

[9] Components in pulsed systems undergo periodic stresses not experienced in steady-state systems. Pulsed reactors also require some form of energy storage to eliminate variations in their electrical output.

The same devices that collect ions at the plasma edge help prevent impurities from entering the plasma. Even small amounts of impurities can cool the plasma by greatly accelerating the rate at which energy is radiated away.

Status.—Two types of devices are being considered for these tasks: *pumped limiters* and *divertors*. A limiter is a block of heat-resistant material that, when placed inside the reaction chamber, defines the plasma boundary by intercepting particles at the plasma edge. A variant, the pumped limiter, combines a limiter with a vacuum pump to remove the material collected by the limiter. A divertor generates a particular magnetic field configuration in which ions diffusing out of the fusion plasma, as well as those knocked out of the vessel walls and drifting towards the plasma, are diverted away and collected by external plates.

Both limiters and divertors are in direct contact with the plasma edge. Although temperatures at the edge are far below the 100-million-degree C temperatures found in the plasma center, these components will nevertheless get very hot. All the energy injected into or produced by the plasma that is not carried away by neutrons or radiated away as electromagnetic energy is eventually deposited on the limiter or divertor plates by electrons and ions. Therefore, these devices must withstand high heat loads under energetic ion and neutral particle bombardment while being exposed to intense neutron radiation. In a fusion environment, they will become radioactive due to neutron-induced reactions and, to a much lesser extent, to permeation with tritium. Their reliability must be high since they will be located deep within the reactor, inside the vacuum vessel, where maintenance will be difficult.

Issues.—A key issue for reaction product and impurity control will be the choice between pumped limiters and divertors. The devices not only have different efficiencies but have different effects on plasma confinement. Limiters are simpler, but divertors may have operational advantages.[10] More R&D is necessary to investigate issues such as the conditioning and cleaning of surfaces in contact with the plasma, the erosion of these surfaces and redeposition of their materials elsewhere in the plasma chamber, the effects of high heat loads, the development of cooling systems, and the degree and effects of tritium permeation.

Burn Control

Description.—When a fusion reactor plasma is ignited, it provides its own heat and no longer depends on external heating. Two opposing tendencies make it difficult to determine how stable, or self-regulating, an ignited plasma will be. An ignited plasma may be inherently unstable due to the strong temperature dependence of the fusion reaction rate. If, for whatever reason, a hot spot forms in the plasma, the fusion reaction rate there will go up. As a result, more fusion power will be generated in that area, heating it further and compounding the original problem.

If the plasma particles mix with sufficient speed, hot spots that form will not persist long enough to grow. If, on the other hand, the mixing is slow, this *thermal instability* might make it very difficult to maintain a steady reaction. Formation and growth of hot spots could cause output power levels to fluctuate considerably, and in the worst case these hot spots could grow until much of the fuel present in the reaction chamber was consumed. The amount of fuel would not be large—at most a few seconds' worth—making this process more of an operational problem than a safety one. The reactor would have to be designed so that it could not be damaged, and its contents not be released, by the maximum amount of energy that could be produced in this way.

Countering this possible instability is a self-regulating mechanism that limits the maximum attainable value of the beta parameter. Any instability that heated the plasma would increase the plasma beta, which is proportional to temperature. However, since the power generated by a fusion reactor is proportional to beta squared, a reactor would probably already be operating at the highest value of beta consistent with good performance. Further increases in beta would degrade plasma confinement and increase energy loss. These increased losses would cool the plasma back down, counteracting the initial instability.

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[10] The H-mode of tokamak operation, in which confinement properties are significantly improved, is seen in tokamaks with divertors. This mode, now thought to depend on processes occurring at the plasma edge, may be difficult to reproduce with limiters.

These beta-limiting processes could maintain a steady reactor power level. The plasma would tend to operate just under the limiting beta value, and, by adjusting the magnetic field or the plasma density, the power level corresponding to the limiting beta value could be controlled.

Status and Issues.—It is impossible, without creating and studying an ignited plasma, to determine how a plasma will behave in the face of the two opposing tendencies described above. Neither the causes of beta-limiting processes nor their effects on the plasma are fully understood in general. More research is necessary before the ability of these processes to stabilize a fusion plasma can be determined.

The processes that control the reaction rate and burn stability of an ignited plasma are probably the most device-dependent and least understood of any aspect of burning plasma behavior.[11] Even for tokamaks, the properties that determine stability have been studied only under conditions well short of ignition; still less is known about the properties of other confinement concepts. If these issues are indeed concept-specific, only limited information from a burning plasma experiment using one confinement concept can be used to predict the behavior of another.

The Fusion Blanket and First Wall

The region immediately surrounding the fusion plasma in a reactor is called the *blanket*; the part of the blanket immediately facing the plasma is called the *first wall*. In some designs, the first wall is a separate structure; most often, however, the first wall refers to the front portion of the blanket that may contain special cooling channels.

The blanket serves several functions. Cooling systems in the blanket remove the heat generated by fusion reactions and transfer it to other parts of the facility to generate electricity. Depending on plant design and materials selection, these cooling systems also might be needed to remove afterheat from the radioactive decay of materials in the blanket after a plant shutdown. In addition, the tritium fuel required by the reactor is produced, or "bred," in the blanket. Furthermore, the blanket must support itself and any other structures that are mounted on it.

The safety of the plant will be greatly influenced by the blanket breeder, coolant, and other subsystems. Since the blanket will perform multiple functions, its development will require an integrated R&D program. This program must have two primary aspects: it must develop the capability to predict the behavior of blanket components and systems under actual reactor usage, and it must develop technologies that can produce fuel and recover energy in the blanket while maintaining attractive economic, safety, and environmental features.

Intense irradiation by neutrons produced in the fusion plasma will make blanket components radioactive, with the level of induced radioactivity depending on the materials with which these components are made. Tritium bred within the blanket will add to the blanket's total radioactive inventory. As the largest repository of radioactive materials in a fusion plant, the blanket will be the focus of environmental and safety concerns.[12]

The discussion below focuses on blankets that would be used in fusion reactors that generate electricity. Reactors used for other purposes, some of which are discussed in appendix A, would have different blanket designs.

Description

Energy Conversion.—The first wall is heated by radiation from the plasma as well as by energy carried by particles leaking out of the plasma. Energetic neutrons produced in the plasma penetrate the blanket, where they slow down and convert their kinetic energy into heat. Coolant circulating within the blanket and first wall transfers this heat to other areas of the plant, where it is used to generate electricity. The coolant also prevents blanket and first wall components from overheating during reactor operation; depending on plant design, coolant also may be needed to prevent overheating after plant shutdown, whether scheduled or emergency. Depending on the level of radioactivity within the blanket and coolant, secondary heat exchangers like those now used in nuclear fission plants may be required to isolate the coolant.

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[11] Argonne National Laboratory, *Technical Planning Activity: Final Report*, op. cit., p. 155.

[12] Plant safety characteristics are discussed further in ch. 5.

Fusion neutrons slow down by colliding with the nuclei of blanket materials, transferring energy to the blanket in the process. Additional heat is also generated in reactions that occur when the neutrons are captured by materials in the blanket. Depending on their energy, the neutrons travel up to several centimeters between collisions. Collisions change the neutrons' directions, and a blanket thickness of from one-half meter to one meter is enough to capture most of the neutron energy.

Tritium Breeding.—Through reactions with fusion neutrons, the nuclei in the blanket can be changed into other nuclei that are either stable or radioactive. In particular, if a fusion neutron is captured by a lithium nucleus, it will induce a reaction that produces tritium (see box 4-B).[13] Therefore, the presence of lithium in the blanket is necessary for tritium breeding.

The number of tritium nuclei produced in the fusion blanket per tritium nucleus consumed in the fusion plasma, called the *breeding ratio*, must be at least 1 for the reactor to be self-sufficient in tritium supply. Accounting for losses and imperfections in the blanket, as well as uncertainties in the data used to calculate tritium breeding rates, this ratio probably should be in the range of 1.1 to 1.2.

Lithium can be contained in the blanket in either solid or liquid form. Lithium metal has a low melting point (186° C) and excellent heat transfer properties, making it attractive as a coolant in addition to its use in breeding tritium. However, in its pure form, liquid lithium can be highly reactive and may pose safety problems in fusion reactors. Liquid lithium's reactivity can be lessened by alloying it with molten lead, but the addition of lead substantially increases the production of undesired radioactive materials in the blanket.

Box 4-B.—Tritium Breeding Reactions

Depending on which isotope of lithium (Li) is involved, either of two reactions can produce tritium in the reactor blanket:

$$n + {}^{6}Li \rightarrow T + {}^{4}He + 4.8 \text{ MeV}$$
$$n + {}^{7}Li + 2.5 \text{ MeV} \rightarrow T + {}^{4}He + n$$

As the first equation shows, the reaction of the ^{6}Li isotope with a neutron (n) produces tritium (T) and helium (^{4}He, or alpha particle), and it releases 4.8 million electron volts (Mev) of energy. In the second equation, the reaction of the ^{7}Li isotope with a neutron requires 2.5 MeV of energy in order to occur. Although ^{6}Li constitutes only 7 percent of natural lithium, it is so much more likely than ^{7}Li to react with a neutron that most of the tritium generated in the blanket results from the ^{6}Li reaction. The energy released in this reaction contributes to the total reactor output.

The neutron that is reemited in the ^{7}Li reaction can be captured in the ^{6}Li reaction, producing an additional tritium nucleus and making it possible to generate tritium at a higher rate than it is consumed in the plasma. The extra neutrons from ^{7}Li reactions also make up for neutrons that escape from the blanket or are absorbed by other substances. Still more neutrons can be produced when neutrons react with substances called neutron multipliers. One of the best neutron multipliers is beryllium (^{9}Be), which reacts with one neutron to produce two:

$$n + {}^{9}Be + 1.6 \text{ MeV} \rightarrow {}^{4}He + {}^{4}He + n + n$$

Liquid metal coolants can be avoided by separating the function of cooling the blanket from that of breeding tritium. A non-lithium-containing fluid can be used as the coolant, and solid lithium-containing compounds can be used to produce tritium. However, solid lithium compounds contain other elements, such as oxygen and aluminum, that would capture some of the fusion neutrons and lower the breeding ratio. To compensate for the lost neutrons, substances called *neutron multipliers* can be added to the blanket. Neutron multipliers convert one very fast fusion neutron to two or more slower neutrons by means of a nuclear reaction.[14]

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[13] Lithium is a reactive metal that does not occur in its pure form in nature. However, chemical compounds containing lithium are found in many minerals and in the waters of many mineral springs. Fuel resources for fusion are discussed in ch. 5.

Recovering the tritium from solid breeder materials is more difficult than from liquid breeders. When tritium is bred in a liquid coolant, the coolant carries the tritium directly outside the blanket where it can be extracted. Tritium produced in solid lithium-containing compounds, on the other hand, must first diffuse out of those compounds before it can be collected and flushed out of the blanket by a circulating stream of helium gas.

Blanket Structure.—The heat loads, neutron fluxes, and radiation levels found in the blanket place stringent requirements on the materials with which the blanket is made. Conditions are most severe at the first wall, which is bombarded by neutron and electromagnetic radiation from the plasma, by neutral particles, and by plasma electrons and ions that escape confinement. First wall issues are similar to many of the issues associated with limiters and divertors (discussed previously in the section on "The Fusion Plasma," under the heading "Reaction Products and Impurity Control"), which undergo even higher heat and particle fluxes than the first wall.

Neutron irradiation introduces two major problems in the blanket materials. First, irradiation can lead to brittleness, swelling, and deformation of the reactor structural materials. During the service lives of first wall and blanket components, each atom in those components will be displaced several hundred times by collisions with fusion neutrons. The amount of radiation damage that the blanket materials can withstand determines component lifetimes and also places an upper limit on reactor power for a blanket of a given size.

Second, neutron irradiation makes the blanket radioactive. Not all the neutrons penetrating the blanket will be captured in lithium to breed tritium. Some will be absorbed by other blanket materials, making those materials radioactive. Other fusion neutrons will penetrate the blanket to make reactor structures outside the blanket radioactive. Since the degree of radioactivity generated within the reactor structure strongly depends on the reactor's composition, development and use of *low-activation* materials that do not generate long-lived radioactive products under neutron bombardment will greatly lessen induced radioactivity.

Due to radiation damage, blanket and first wall components in a fusion reactor will require periodic replacement. After their removal, the old components will constitute a source of radioactive waste.[15]

Impact on Fusion Reactor Design.—Although the blanket and first wall components themselves may not represent a large fraction of the cost of a fusion reactor, blanket design has a substantial influence on total reactor cost. The blanket thickness (along with that of the shield, described below) determines the size and cost of the magnets, which are substantially more expensive than the blanket. The blanket coolant temperature determines the overall efficiency with which the plant converts fusion power into electricity, directly affecting the cost of electricity. The selection of materials in the blanket determines the amount of long-term radioactive waste and the amount of heat produced by radioactive decay in the blanket after plant shutdown; both the waste and the heat affect the reactor's environmental and safety aspects. Finally, the ability of the blanket materials to withstand heat loads and neutron irradiation levels determines the amount of fusion power that can be generated in a plant of a given physical size, which has a significant effect on reactor size and cost and on its behavior during accidents.

Status and Issues

A wide variety of designs have been proposed for the blanket and first wall. However, since the fusion research program has concentrated to date primarily on plasma science issues, relatively little experimental work has been done on blanket design or fusion nuclear technologies in general. As the program moves from establishing scientific feasibility to demonstrating engineering feasibility, engineering issues will become much more important.

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[14] Beryllium and lead are commonly used in reactor studies as neutron multipliers.

[15] According to Argonne National Laboratory, *Technical Planning Activity: Final Report*, op. cit., p. 283, the amount of long-lived (more than 5 years) radioactive waste depends primarily on the amounts of copper, molybdenum, nitrogen, niobium, and nickel used in the blanket. Radioactivity levels, radioactive wastes from fusion reactors, and low-activation materials are discussed further in ch. 5.

Tritium Self-Sufficiency.—Engineering designs must be developed to produce tritium at a rate equal to the rate of consumption in the plasma plus an additional margin. The extra tritium, 10 to 20 percent of the amount consumed in the plasma, is needed to compensate for losses due to radioactive decay and to provide the initial inventory to start up new reactors. Improvements in calculating neutron flow through the reactor structure and in collecting additional basic nuclear data such as reaction rates are necessary to develop adequate engineering designs. Experimental verification of the calculation methods and data is also required to demonstrate tritium self-sufficiency.

Structural Materials.—Structural materials in the first wall and deeper in the blanket must be developed that can withstand neutron-induced effects such as swelling, brittleness, and deformation. Stainless steel alloys already have been identified that appear to show adequate performance under neutron fluxes at the low end of those expected in a reactor. However, these materials produce more radioactive products than may be desirable for commercial reactors. Developing low-activation materials that also have acceptable physical properties under irradiation remains a significant challenge. The task will require further basic research in materials science as well as progress in materials technology.

Non-Structural Blanket Materials.—The tritium-breeding properties of various lithium-containing materials must be studied and compared. The choice between solid and liquid breeder materials, in particular, will greatly affect overall blanket design. In addition to lithium, other materials may be required in the blanket such as neutron multipliers and *moderators* (which slow down neutrons to make them more easily absorbed in the blanket). Insulators, or materials that do not conduct electricity, also may be required for high radiation areas inside the reactor. Since a typical effect of radiation damage on insulators is to increase electrical conductivity, developing materials that will remain insulators under high radiation fluxes is a challenging task.

Special Materials.—Other materials requirements for a fusion reactor may include special materials to coat plasma-facing surfaces to minimize their effect on the plasma, coatings or claddings used to form barriers to contain tritium, and advanced superconducting magnet materials (described in the section on magnets, below). Many of the specific requirements for these materials have not yet been determined.

Compatibility.—Certain combinations of materials, each suitable for a particular task, may in combination prove unacceptable in a reactor design. For example, liquid lithium reacts violently with water, so a liquid lithium-cooled blanket design would probably prohibit use of water as an additional coolant.

Tritium Permeation and Recovery.—Once produced inside the blanket, tritium must be recovered and removed. However, tritium will permeate many materials that are continuously exposed to it. Its interactions with blanket materials under the conditions inside a fusion reactor will have to be understood. In particular, tritium may be difficult to collect from solid breeder materials.

Liquid Metal Flow.—Liquid metal coolants in a fusion reactor will be subject to strong magnetic fields created both by the plasma and by external magnets. Liquid metals are conductors of electricity; when electrical conductors move through magnetic fields, voltages and currents are generated.[16] The currents induced in the coolant, in turn, are subject to forces from the magnetic field that oppose the motion of the coolant, increasing coolant pressure and adding to the power required for pumping.

The Shield

Description and Status

Since many neutrons will penetrate all the way through the blanket during fusion reactor operation, a shield may be required between the blanket and the magnet coils.[17] The shield may be composed of materials such as steel and water, will probably contain a circulating coolant, and would have a thickness from tens of centimeters to over a meter. The shield would provide extra protection to the magnets and could reflect escaping neutrons back into the blanket to improve the efficiency of tritium breeding. Additional shielding would probably surround the entire reactor core, perhaps in the form of thick walls for the enclosing building.

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[16] This process is the basis of electrical generators.

Most existing fusion experiments have not been designed to use tritium and are incapable of generating significant amounts of fusion power. Consequently, shielding has generally not been an important issue for the research program. It has, however, been a factor in the design of devices such as TFTR and the Joint European Torus that are intended to use tritium. As future machines are designed that will generate appreciable amounts of fusion power, shielding will become more important.

Issues

The intensity of the incident neutron radiation; the size, shape, and effectiveness of the shield; and the permissible levels of neutron irradiation penetrating the shield must all be determined to evaluate shielding requirements. As improved magnet materials are developed that are less sensitive to neutron radiation, shielding requirements for plant components will lessen. However, protection of plant personnel alone will require substantial shielding.

The Magnets

Description

The external confining magnetic fields in a fusion reactor are generated by large electric currents flowing through magnet coils surrounding the plasma. These magnets must withstand tremendous mechanical forces.

The most important choice concerning design of the magnets is whether they will be made of superconducting materials or of conventional conductors such as copper. Copper is an excellent conductor of electricity but nevertheless has sufficient resistance to electric currents that a great deal of power is wasted as heat when the magnet is running. This heat must be removed by cooling systems. Superconducting coils lose all resistance to electricity when cooled sufficiently; below a temperature called the *critical temperature*, their magnetic fields can be sustained without any additional power. However, power is required to establish the fields initially, and a small amount of refrigeration power is required to keep superconducting magnets at their operating temperature. No heat is generated inside a superconducting magnet, but heat that leaks in from the outside must be removed.

Although recent discoveries could revolutionize the field (see "Issues" section below), all superconducting materials that have so far been used in large magnets have critical temperatures within about 20° K of absolute zero. The only substance that does not freeze solid at these temperatures is helium, and the only way to cool superconducting magnets to these temperatures is to circulate liquid helium through them. Use of liquid helium makes superconducting magnets more complicated and expensive to build than copper magnets; superconducting magnets also require thicker shields. However, superconducting magnets require much less electricity to run, substantially lowering their operating costs.

Conceptual design studies typically have shown that the operational savings from using superconducting magnets in commercial fusion reactors would more than compensate for their higher initial cost. However, there may be exceptions, especially for confinement concepts with higher beta values that are able to confine fusion plasmas at lower magnetic field strengths. At lower field strengths, copper magnets, which do not require as much shielding as superconducting magnets, can be made to fit more closely around the plasma chamber. The resultant reduction in size of the magnet/shield combination might reduce its cost enough to outweigh the operational inefficiencies of copper magnets.

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[17] If the magnets are superconducting, the shield will be required. If they are made of copper, the shield may not be necessary. However, without a shield, the coils would require periodic replacement. See the following section on magnets.

Whereas the magnets in future fusion reactors will operate for long pulses, if not continuously, magnets in present-day fusion experimental facilities generally operate only for several seconds at a time. For pulses this short, the cost of electricity is less of a factor in determining magnet design, making the simpler construction of copper magnets preferable in most cases. A notable exception is the MFTF-B device at Lawrence Livermore National Laboratory, which was built with superconducting magnets because copper coils would have been prohibitively expensive to operate even for 30-second pulses.

Status

The first fusion device built with superconducting magnets was the Soviet T-7 tokamak, completed 7 years before any Western fusion device using superconducting magnets. The Soviets are now building T-15, a much larger superconducting tokamak. Difficulties with the T-15 magnets have been among the reasons that the project's completion has been delayed for several years; however, these difficulties apparently have been resolved. The Tore Supra tokamak being built in France will also use superconducting magnets and will probably exceed the parameters of T-15.[18] In the United States, MFTF-B was completed in 1986; its superconducting magnets have been successfully tested at their operating conditions. Overall, DOE considers U.S. magnet development to be comparable to that in Europe and Japan and ahead of that in the Soviet Union.[19]

Generally, magnet development has been associated with individual fusion confinement experiments rather than with facilities dedicated specifically to magnet development. A major exception is the Large Coil Task, an international program to build and test superconducting magnets. Magnets developed through the Large Coil Task have worked very well and have exceeded their original design specifications.[20]

Issues

Recent discovery of new superconducting materials with critical temperatures far above those of previously known materials, and possibly with the capability to reach very high magnetic field strengths, will have a profound impact on a great many fields, including fusion. Materials have been identified with critical temperatures higher than the 77 Kelvin (−196° C) threshold that would permit use of liquid nitrogen as a refrigerant. Liquid nitrogen is cheaper and easier to handle than liquid helium, and its use could reduce the cost and complexity of superconducting magnets.

However, the discovery of these "high-temperature" superconductors does not necessarily mean that they can soon be utilized in fusion applications. Little is known about the physical processes underlying superconductivity in these materials, and they present great engineering challenges. They are difficult to fabricate into magnet coils, and they may not be able to withstand the forces exerted in fusion magnets. Although their current-carrying capability is improving, they may not be able to carry high enough currents under high magnetic fields to be useful in large-scale magnets. Moreover, their response to neutron irradiation is not known. If these materials are highly susceptible to radiation damage, their use in fusion magnets could be difficult. Conversely, if they proved more resistant to radiation effects than previous superconducting materials, thinner shields and correspondingly smaller magnets could be used.

Further research is required to see whether the new superconducting materials can be used in practical applications. The great economic advantage that they would have in numerous applications ensures that much of this research will be undertaken independently of the fusion program. However, fusion does have particular requirements for large, high-field magnets that may not otherwise be investigated.

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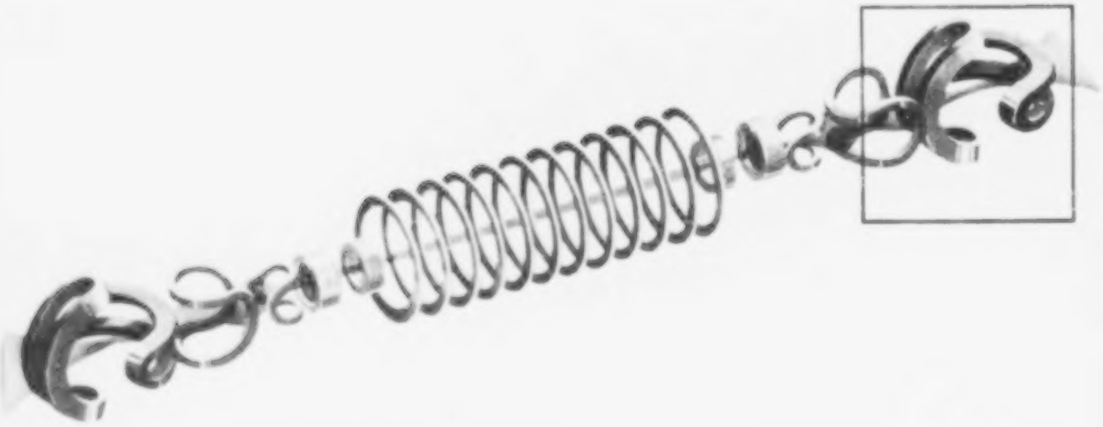
[18] Information on Soviet tokamak development is from an oral presentation on "Assessment of Soviet Magnetic Fusion Research" by Ronald C. Davidson, Director of the Plasma Fusion Center, Massachusetts Institute of Technology, to the Magnetic Fusion Advisory Committee, Princeton, NJ, May 19, 1987.

[19] International comparisons are from a presentation by R.J. Dowling, Director of the Division of Development and Technology, Office of Fusion Energy, U.S. Department of Energy, to the Energy Research Advisory Board, Sub-Panel on Magnetic Fusion, Washington, DC, May 29, 1986.

[20] The Large Coil Task is discussed further in ch. 7.



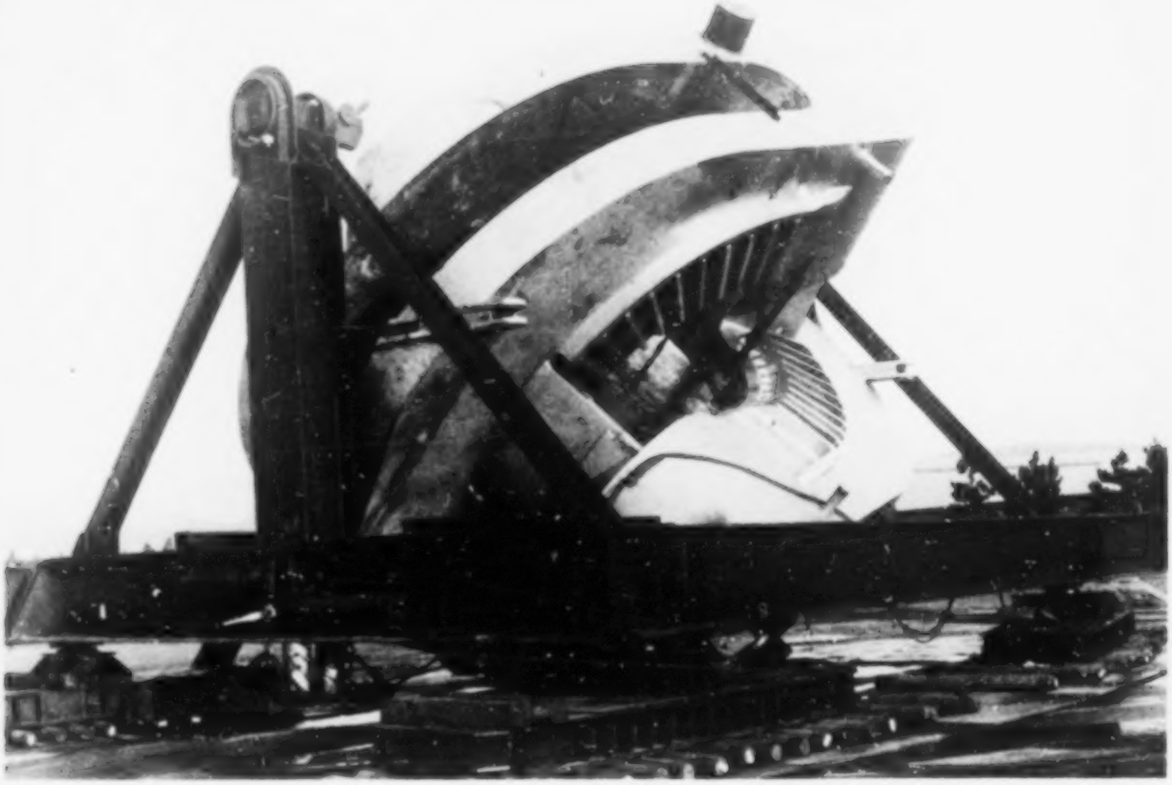


Photo credit: Lawrence Livermore National Laboratory

375-ton superconducting magnet being moved to the east end cell of MFTF-B for installation. This magnet's location within MFTF-B is shown at top.

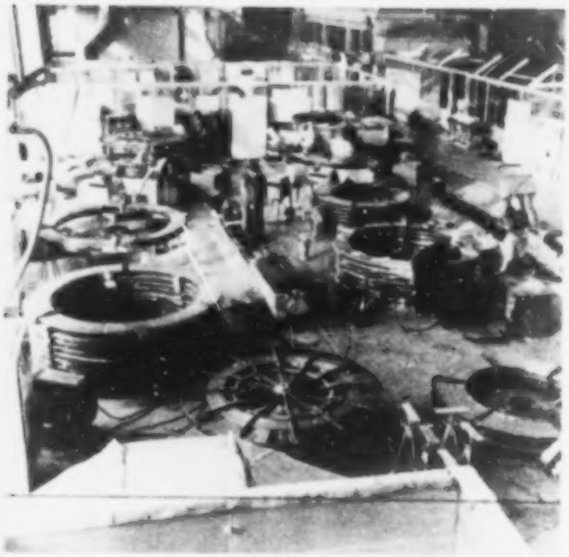


Photo credit: Fusion Power Associates

Superconducting magnet coils for the Soviet T-15 tokamak being wound at the Efrenov Institute in Leningrad.

Issues for superconducting fusion magnet materials include further development and investigation of the new high-temperature materials. If these new materials prove unacceptable for fusion, improvements in the strength, workability, and maximum current capacity of the previously known superconductors will be important. Issues for copper magnets include fully exploiting copper's strength and developing joints (needed to assemble and maintain the magnet) that can carry large electric currents.

Fuel Processing

Description

Tritium fuel contained in the exhaust from the plasma, or generated in the reactor blanket, must be extracted, purified, and supplied back to the fueling systems for injection into the plasma. Considerable experience has been developed in handling tritium, particularly within the nuclear weapons program, making tritium technology more highly developed than many of the other nuclear technologies required for fusion. However, this experience is applicable primarily to handling the tritium in a fusion reactor once it has been produced and separated. The task of extracting tritium from a blanket under reactor conditions while at the same time generating electric power with high efficiency has yet to be done.

Status

To acquire experience with tritium handling for fusion applications, DOE has built and is operating the Tritium Systems Test Assembly (TSTA) at Los Alamos National Laboratory. A prototype of the tritium processing and handling facilities needed for a full-scale fusion reactor, TSTA includes plant safety equipment such as a room atmosphere detritiation system. TSTA operators have developed system maintenance procedures that minimize or eliminate tritium release. This system, however, does not duplicate the production or extraction of tritium from a fusion blanket.

Issues

Specific issues involved with tritium processing include monitoring, accountability, and safety. Being radioactive, tritium cannot be allowed to diffuse out of the reactor structure. If tritium collects on inaccessible surfaces within the reactor, it cannot be completely recovered, and it will make those surfaces radioactive. Developing tritium processing systems will require additional research in measuring basic tritium properties such as diffusivity, solubility, and oxidation chemistry. Safety needs include developing and maintaining the capability to contain and recover tritium from air and from water coolants (if any) in the event of tritium contamination.

Remote Maintenance

Due to their inventory of radioactive tritium and the activation of their structural components, the interior of all subsequent fusion experiments that burn D-T will become too radioactive for hands-on maintenance. Therefore, remote maintenance is a key issue not only for future power reactors, but also for near-term D-T experiments. Nearly all aspects of the research program, from design of experiments to operation and maintenance to decommissioning, will be affected by the need for remote maintenance.

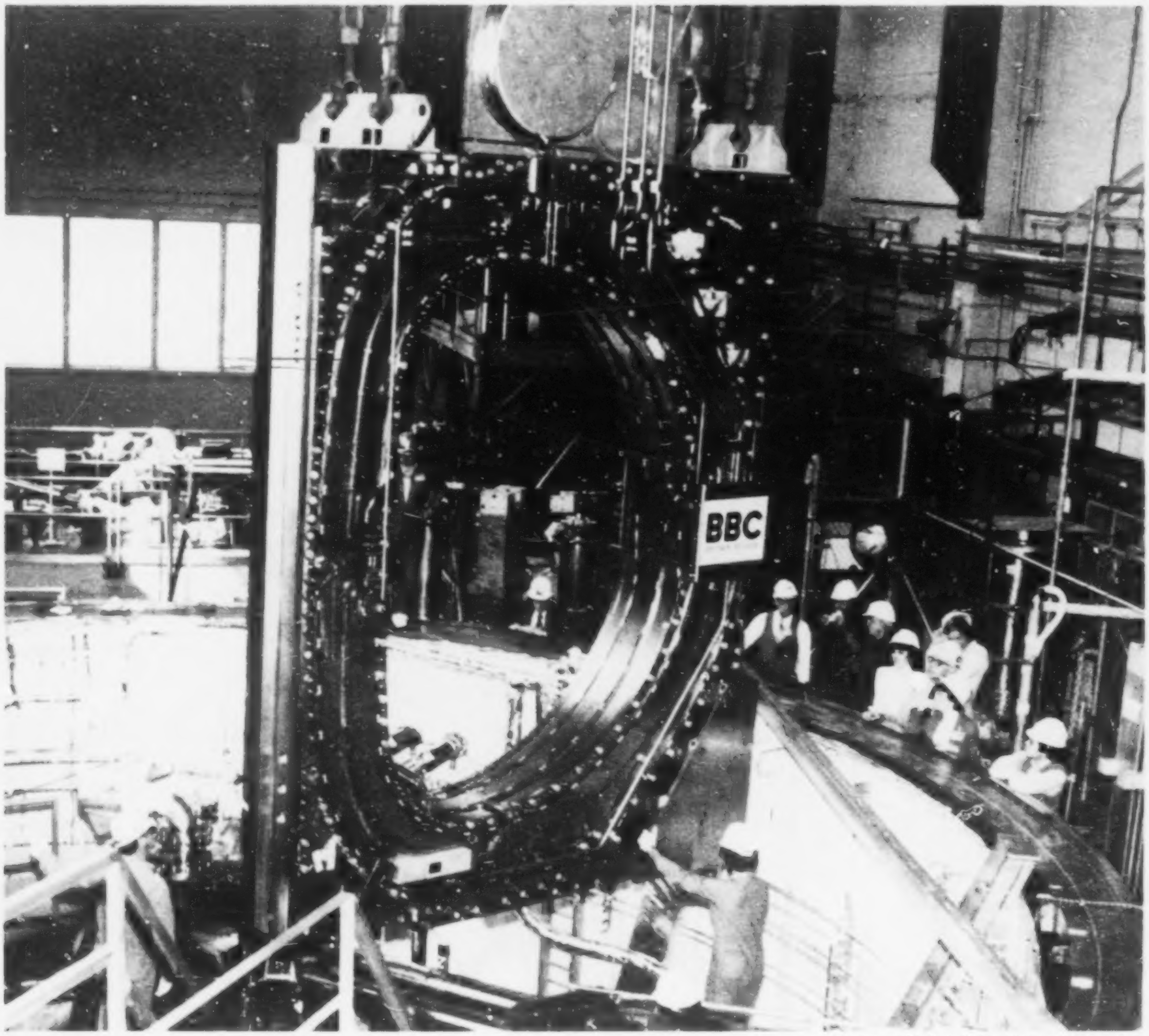


Photo credit: Oak Ridge National Laboratory

The Swiss superconducting magnet coil being installed in the International Fusion Superconducting Magnet Test Facility (Large Coil Task) at Oak Ridge National Laboratory.

The fusion program at present is relying on activities outside the fusion community for general development of remote maintenance equipment. Much work in remote manipulation and remote maintenance has been done, but some applications are likely to be unique to fusion and will require special development. Remote maintenance requirements for fusion facilities will include transporters able to move heavy loads (over 100 tons) with precision alignment; manipulators made of nonmagnetic material that can operate under high vacuum conditions; and rapid and precise remote cutting, welding, and leak detection equipment. The first challenge in this field

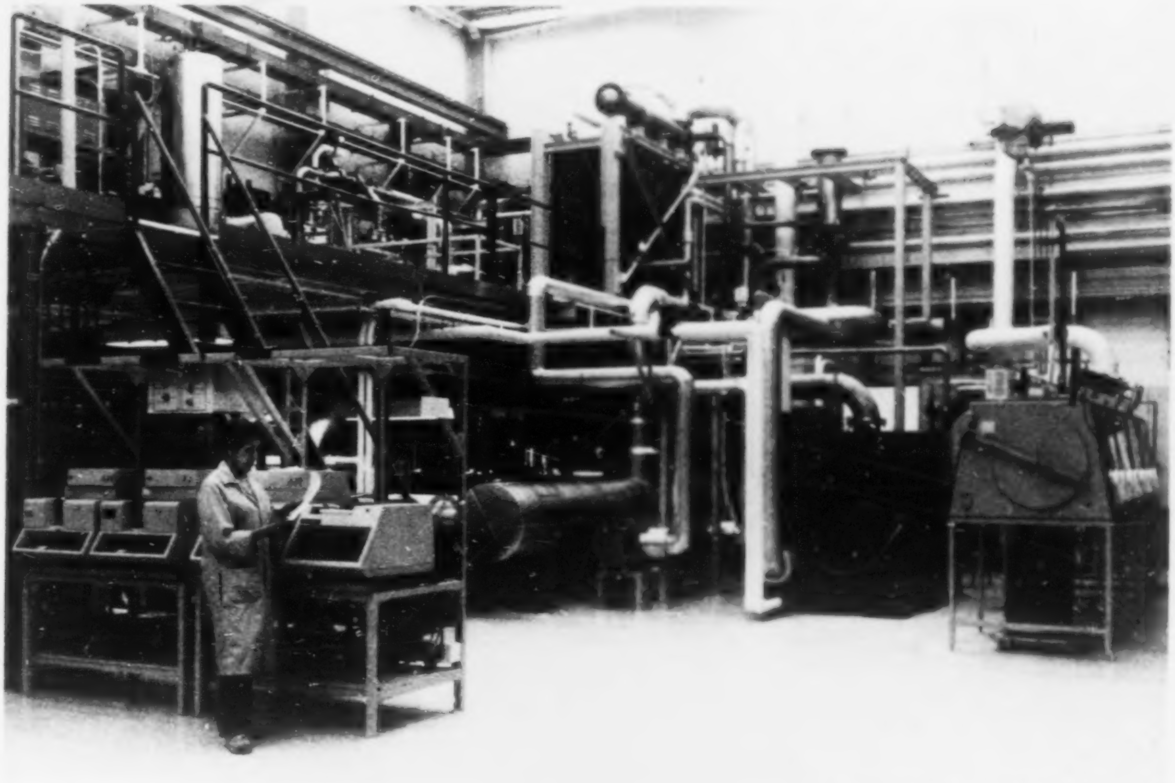


Photo credit: Los Alamos National Laboratory

The Tritium Systems Test Assembly at Los Alamos National Laboratory

will be identification of the remote maintenance requirements for near-term facilities and the development of any necessary equipment. Subsequently, needs for test facilities and reactors must be identified and assessed.

ADVANCED FUEL AND ENERGY CONVERSION CONCEPTS

Even though the fusion power core systems described in the previous section have not yet been developed, researchers already are designing reactors using more advanced concepts. Improvements described below are not mere refinements of the systems already described; they are qualitatively new features that may be much more attractive. In general, these improvements involve use of either advanced fuels or advanced methods of converting fusion energy into useful forms.

Advanced Fuels

The fusion power core described in the previous section uses D-T fuel because it is by far the most reactive of all potential fusion fuels. This reactivity can be increased still further by aligning the internal spins of the deuterium and tritium nuclei, a technique known as *spin polarization*. If the spins can be aligned initially, the magnetic field of the fusion reactor will tend to keep them in alignment. Therefore, research is ongoing at Princeton Plasma Physics Laboratory to develop intense sources of spin-polarized fuel.

The principal disadvantage of D-T fuel is that the D-T reaction produces energetic neutrons that cause radiation damage and induce radioactivity in reactor structures. Moreover, reactors using D-T must breed their own tritium, substantially adding to reactor complexity and radioactivity levels. For these reasons, the possibility of using other fuels in fusion reactors is being investigated.

Fuels other than D-T require higher temperatures and Lawson confinement parameters to reach ignition and higher beta values to perform economically. Achieving these parameters will require stronger magnetic fields, higher plasma currents, and substantial improvements in other plasma technologies beyond those needed to reach ignition with D-T fuel—a task that in itself has not yet been accomplished. However, reactions that use advanced fuels would have a number of advantages:

- They would require little to no tritium, reducing or eliminating the need for the blanket to breed tritium and permitting a much wider range of blanket designs. Tritium inventories would be smaller and the consequent radioactivity levels would be lower.
- They would generate fewer and lower energy neutrons, alleviating radiation damage and minimizing radioactive wastes.
- They might permit the use of more efficient methods to generate electricity from fusion energy. In advanced fuel fusion reactions, more energy is released in the form of energetic charged particles, such as protons or alpha particles, than is the case in the D-T reaction. Therefore, these advanced fuels may be amenable to various techniques that generate electricity directly from the fusion plasma or from plasma-generated radiation without having to first convert the energy into heat. (See the following section on "Advanced Energy Conversion.")

Table 4-8 presents five fusion fuel cycles, including the "baseline" D-T cycle and four possibilities for advanced fuel cycles. Of the advanced cycles, the D-^{3}He cycle is currently drawing the most attention within the fusion community. The primary reaction produces no neutrons, and neutrons resulting from corollary D-D reactions can be minimized by using a mixture consisting mostly of ^{3}He or by using spin-polarization.[21]

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[21] Deuterium, being relatively scarce in a ^{3}He-rich mixture, would be much more likely to react with a ^{3}He nucleus than with another deuterium nucleus, making D-D reactions relatively rare. However, one consequence of this mode of operation, in addition to minimizing neutron generation, would be the lessening of output power since most of the ^{3}He nuclei would be unable to find D nuclei with which to react. Increasing the ratio of D to ^{3}He to more nearly equal proportions, therefore, would increase both the output power and the neutron generation.

Spin polarization suppresses the D-D reaction rate because, unlike the D-T reaction, two deuterium nuclei whose spins are aligned are less likely to react with each other.

Table 4-8.—Fusion Fuel Cycles[a]

Cycle	Primary reaction	Percent of energy carried by charged particles
D-T cycle	$D + T \rightarrow {}^4He + n + 17.59$ million electron volts (MeV) [D = deuterium; T = tritium; ^{4}He = alpha particle, or helium nucleus]	20%
D-D cycle	$D + D \rightarrow p + T + 4.03$ MeV $D + D \rightarrow {}^3He + n + 3.27$ MeV [p = proton; ^{3}He = helium isotope with one less neutron than ^{4}He]	62%[b]
D-^{3}He cycle	$D + {}^3He \rightarrow {}^4He + p + 18.34$ MeV	up to 98%[c]
D-^{6}Li cycle	$D + {}^6Li \rightarrow$ 5 different reactions [^{6}Li = isotope of lithium]	over 65%
p-^{11}B cycle	$p + {}^{11}B \rightarrow {}^4He + {}^4He + {}^4He + 8.66$ MeV [^{11}B = isotope of boron]	almost 100%[d]

[a] Presented in order of increasing difficulty; the last reaction is from 100 to 10,000 times harder to ignite than the first one, depending on temperature.

[b] Sixty-two percent is the fraction of the energy carried off by charged particles, assuming that the intermediate reaction products (T and ^{3}He) react further via D-T and D-^{3}He reactions. With these additional reactions, the full reaction is

$$6D \rightarrow p + p + n + n + {}^4He + {}^4He + 43.23 \text{ MeV}$$

[c] Ninety-eight percent can be attained for mixtures lean in D and rich in ^{3}He (see footnote 21 in main text, above).

[d] A low energy (0.15 MeV) neutron is produced in the secondary reaction $^4He + {}^{11}B \rightarrow n + {}^{14}N + 0.158$ MeV [^{14}N = isotope of nitrogen].

SOURCE: U.S. Department of Energy, *Background Information and Technical Basis for Assessment of Environmental Implications of Magnetic Fusion Energy*, DOE/ER-0179, August 1983, p. 2-3 (table 2.1) and pp. 2-24 to 2-27, including table 2.2.

However, the D-^{3}He reaction is much more difficult to start than the D-T reaction. The minimum temperature required to ignite D-^{3}He is several times higher than that needed for D-T; the minimum confinement parameter is about 10 times higher. Given that the requirements for igniting D-T have not yet been experimentally achieved, attaining conditions sufficient to ignite D-^{3}He is considerably farther off. On top of its technological requirements, ^{3}He is scarce. It is an isotope of helium with one fewer neutron than natural helium (^{4}He), and it occurs on earth only as the end-product of tritium decay. The only way to collect ^{3}He is to make tritium and wait for it to decay or to breed ^{3}He as the product of another advanced fuel fusion reaction, the D-D reaction. Due to the scarcity of ^{3}He, the D-^{3}He reaction has been considered primarily an academic curiosity until recently.

Today, a resurgence of excitement about ^{3}He comes with the discovery that it is found in substantial amounts in the uppermost layers of soil on the moon. Analysis of moon rocks brought back by the Apollo missions shows that ^{3}He, which is constantly emitted by the sun and carried by the solar wind, is deposited and retained in the lunar surface. In principle, a rocket with the cargo volume of the space shuttle could carry back enough liquid ^{3}He to generate all the electricity now used in the United States in one year. Of course, the technology to recover ^{3}He from the moon would not be available for decades, and the energy and capital investment required to mine, refine, liquefy, and transport the ^{3}He have yet to be evaluated.[22]

Advanced Energy Conversion

Despite the very high-level technology in the fusion core, a baseline fusion reactor would generate electricity in much the same way that present-day fossil fuel and nuclear fission powerplants do. Heat produced in the reactor would be used to boil water into steam, which would pass through turbines to drive generators. Through this process, about 35 to 40 percent of the energy produced in the fusion reaction would be converted into electricity, with the remainder discharged as waste heat. This efficiency, roughly the same as that of fossil fuel and nuclear fission generating stations, is determined primarily by the process of generating electricity from the energy in the steam. Efficiency could be raised if advanced, high temperature materials in the blanket and first wall of a fusion reactor permitted higher coolant temperatures to be used.

If the intermediate step of heating steam could be bypassed, a higher percentage of the energy released in fusion reactions could be converted into electricity. Several techniques to integrate generation of electricity directly into the fusion power core have been conceived. One of these, applicable to D-T reactors as well as to advanced fuel reactors, would convert energy carried off by escaping charged particles directly to electricity by collecting the particles on plates. This technique is most applicable to open confinement concepts, in which charged particles can be allowed to escape along magnetic field lines.

Other techniques, which can work with closed confinement concepts, require plasma temperatures significantly higher than the 10- to 15-kiloelectron-volt D-T ignition temperatures. Very hot plasmas radiate more energy away in the form of microwave radiation than cooler plasmas do,[23] and it appears that this radiation could be captured at the first wall or in the blanket and converted directly into electricity. These "direct conversion" techniques would be better suited to advanced fuels, which not only burn at higher temperatures than D-T but also produce most of their energy in the form of energetic charged particles. Unlike neutrons, which escape from the plasma without heating it, charged particles are retained within the plasma. The D-T reaction, in which only 20 percent of the energy is given to charged particles, is less suitable for techniques that recover energy directly from the plasma.

Several direct conversion techniques that may convert well over 35 percent of the fusion energy to electricity have been identified. Until they can be tested experimentally under conditions similar to those in an advanced fusion reactor, they must be considered speculative. Nevertheless, they provide a tantalizing goal.

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[22] Use of lunar ^{3}He is discussed in "Lunar Source of ^{3}He for Commercial Fusion Power," by L.J. Wittenberg, J.F. Santarius, and G.L. Kulcinski, *Fusion Technology* 10(2):167, 1986.

[23] See item 2 in box 4-A, "Plasma Energy Loss Mechanisms."

RESEARCH PROGRESS AND FUTURE DIRECTIONS

In 35 years of fusion research, the technological requirements for designing a fusion reactor have become clearer, and considerable progress has been made towards meeting them. Improved understanding, based on both experiments and increased computational ability, is providing much of the predictive capability needed to design, and eventually to optimize, future plasma experiments and fusion reactors.

Major advances in plasma research have been made possible by progress in tokamak plasma technologies:

- By the 1960s, experiments demonstrated the crucial importance of attaining high vacuum and low impurity levels in the plasma to achieve high densities, temperatures, and confinement times.
- In the mid-1970s, neutral beam technology was first used to heat plasmas to temperatures several times higher than those previously attained. High-performance, high-field copper magnets were used to obtain high Lawson confinement parameters in compact tokamak plasmas.
- The development in the late 1970s of pellet injectors to fuel plasma discharges led to further advances in plasma density and confinement. Development of the poloidal divertor at about the same time led to the discovery of the "H-mode," a mode of tokamak behavior that was not subject to degraded confinement when auxiliary heating was used.
- In the early 1980s, advances in high-power radiofrequency technology gave experimenters new tools to modify the temperature, current, and density distributions within the plasma. Much of this new capability has yet to be exploited.

These accomplishments have contributed to the steady progress in plasma parameters plotted in figure 4-14. Figure 4-14(a) shows the product of the temperature, density, and confinement time that has been achieved simultaneously in various experiments over the last 20 years. Since all three of these parameters must be high simultaneously for the product to be high, this product provides a rough measure of how well these three requirements have been simultaneously achieved.

The next figure, 4-14(b), plots the temperature alone and compares it to the minimum temperature below which neither breakeven nor ignition can occur no matter how high the density and confinement time. The TFTR point shows temperatures well into the reactor regime and far above that needed for ignition. However, the fact that the corresponding TFTR point in figure 4-14(a) is below the ignition threshold indicates that high temperature is not sufficient; the product of density and confinement time must also be high for ignition.

Figure 4-14(c) shows progress in the parameter beta, the ratio of plasma pressure to magnetic field pressure. Note that devices that have achieved high values on one of the three plots often have not been the ones that have gotten the highest values in others. Future devices will have to achieve high values in all areas simultaneously.

The Technical Planning Activity

The technological issues to be resolved before fusion's potential as a power producer can be assessed have been examined in detail in the Technical Planning Activity (TPA), an analysis commissioned by DOE's Office of Fusion Energy and coordinated by Argonne National Laboratory.[24] Over 50 scientists and engineers from the fusion community identified and analyzed the tasks and milestones that constitute the research needed to reach the goal of the DOE fusion program: the establishment of the "scientific and technological base required to carry out an assessment of the economic and environmental aspects of fusion energy."[25] According to DOE's assignment to TPA, the assessment of fusion would be culminated by the construction and operation of "one or more integrated fusion facilities . . . in the post 2000 period."[26]

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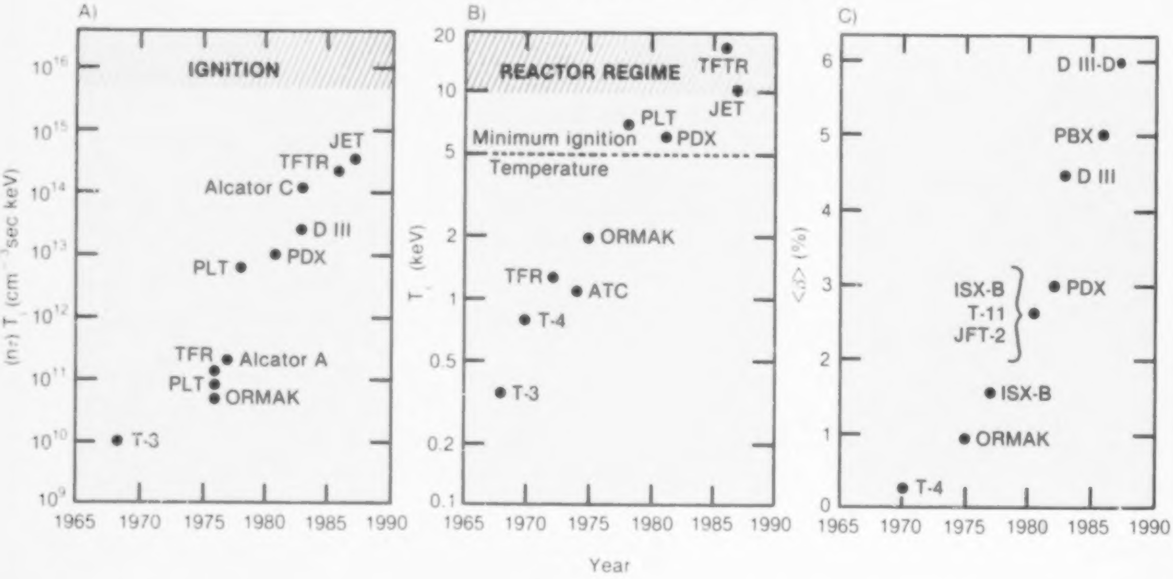
[24] Argonne National Laboratory, *Technical Planning Activity: Final Report*, op. cit.

[25] Ibid., "Technical Planning Activity Mission Statement," p. 348

[26] Ibid.

Figure 4-14.—Progress in Tokamak Parameters



(A) $n\tau T_i$, representing the simultaneous achievement of the three parameters—density, ion temperature, and confinement time—needed to produce fusion power

(B) T_i = ion temperature

(C) $<\beta>$ = beta = ratio of plasma pressure to magnetic field pressure; provides a measure of the efficiency with which the magnetic fields are used

SOURCE: Updated from National Research Council, *Physics Through the 1990s: Plasmas and Fluids* (Washington, DC: National Academy Press, 1986), figure 4.6, p. 160.

The nature of an integrated fusion facility is not specified by either DOE or TPA. The TPA report describes it only as "the beginning of the commercialization phase of fusion" that could "perhaps" take the form of a demonstration power reactor.[27] The decision to proceed with an integrated facility is scheduled in the TPA report in the year 2005.

Key Technical Issues and Facilities

DOE defines four "key technical issues" that must be resolved: magnetic confinement systems, properties of burning plasmas, fusion materials, and fusion nuclear technology.[28] For each of these issues, TPA set technical goals and determined requirements for facilities that could reach these goals.

Magnetic Confinement Systems

The key issue in confinement systems is the development of confinement concepts that would be suitable for commercial fusion reactors. Progress here will require that a series of facilities be built for whichever concepts are judged worthy of further development. A preliminary experiment that investigates basic characteristics of a new concept can be done for a few million dollars or less. An experiment that looks promising can be followed up by a larger "proof-of-concept" experiment, costing up to tens of millions of dollars; such a device would explore the scaling properties of the concept and determine whether it offers the potential for extrapolation to a reactor.

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[27] Ibid., p. 26. On p. 11 of the TPA report, table S.2 provides "representative goals" for an integrated fusion facility (IFF) and for a commercial power reactor. Comparing the two sets of goals shows that the IFF falls well short of commercial performance. It would only produce from one-sixth to one-third the heat generated by a commercial-scale reactor, and it would have considerably lower availability and shorter lifetime than a commercial plant. The IFF described by these parameters, therefore, could not be considered to be a "demonstration" power reactor.

[28] U.S. Department of Energy, Office of Energy Research, *Magnetic Fusion Program Plan*, DOE/ER-0214, February 1985, p. 6.

If the results are promising, a "proof-of-principle" experiment would then be required to provide confidence that the concept could be scaled up to reactor-level conditions. The JET, TFTR, and JT-60 tokamaks are in this category. They are not themselves reactor-level devices, but they will enable decisions to be made about whether to proceed to the final stage of concept development: demonstration of reactor-level plasma conditions, including fueling, burn control, ash removal, and other functions necessary for reactor operation. No reactor-level devices have yet been built for any concept, including the tokamak.

Cost is very difficult to estimate for a future proof-of-principle or reactor-level device. The TPA report estimates costs ranging from 100 million to several hundred million dollars or more.[29] The costs of the existing JET, TFTR, and JT-60 devices range between $600 million and $950 million dollars,[30] but these devices perform many functions in addition to proof-of-principle for the tokamak concept. There is no reason to think that proof-of-principle devices for other confinement concepts would be as expensive. A reactor-scale device for a particular concept would have more stringent technical requirements than its proof-of-principle device and presumably would be more expensive. However, the cost of a reactor-level device depends on whether it would serve other functions such as the long-pulse burn, nuclear technology demonstration, or system integration functions discussed below.

In addition to generic device requirements for selected alternate confinement concepts, TPA also set a requirement for additional tokamaks to investigate features such as shaped plasmas (to follow up on the PBX-M and D III-D results discussed in the earlier sections "Advanced Tokamak," p. 59, and "Beta," p. 70), steady-state tokamak operation, and high-magnetic-field approaches to tokamak confinement.[31]

Properties of Burning Plasmas

Some of the most critical scientific issues yet to be resolved in the fusion program involve the behavior of ignited, or burning, plasmas. These issues include the effects of self-heating on confinement and the effects of energetic alpha particles on plasma stability, burn control, and fueling. Effects such as these, which existing experiments cannot yet address, can profoundly influence fusion's feasibility. TFTR may be able to provide some information about the effects of alpha particle generation if it attains near-breakeven conditions in D-T operation. However, TFTR does not have the capability to reach ignition and therefore will not be able to resolve burning plasma issues definitively. The European JET device should also have the capability to reach and perhaps exceed breakeven, but it too will not be able to resolve many of the burning plasma issues.

According to TPA, two different tasks are required to study burning plasma issues fully. One is a short-pulse ignition demonstration to create a self-sustaining fusion reaction. The second is a long-burn demonstration to maintain a self-sustaining fusion reaction long enough to study effects such as the evolution of the plasma under steady-state burn and the buildup of reaction products. These two tasks could be done in separate facilities or in the same facility.

For fiscal year 1988, DOE has requested funds to start building a Compact Ignition Tokamak (CIT) to study short-pulse ignition issues (figure 4-15). This device, to be located immediately adjacent to TFTR at Princeton Plasma Physics Laboratory, is anticipated to cost about $360 million (including diagnostic equipment and associated R&D) and will take advantage of existing equipment at the site. Operation is scheduled to be-

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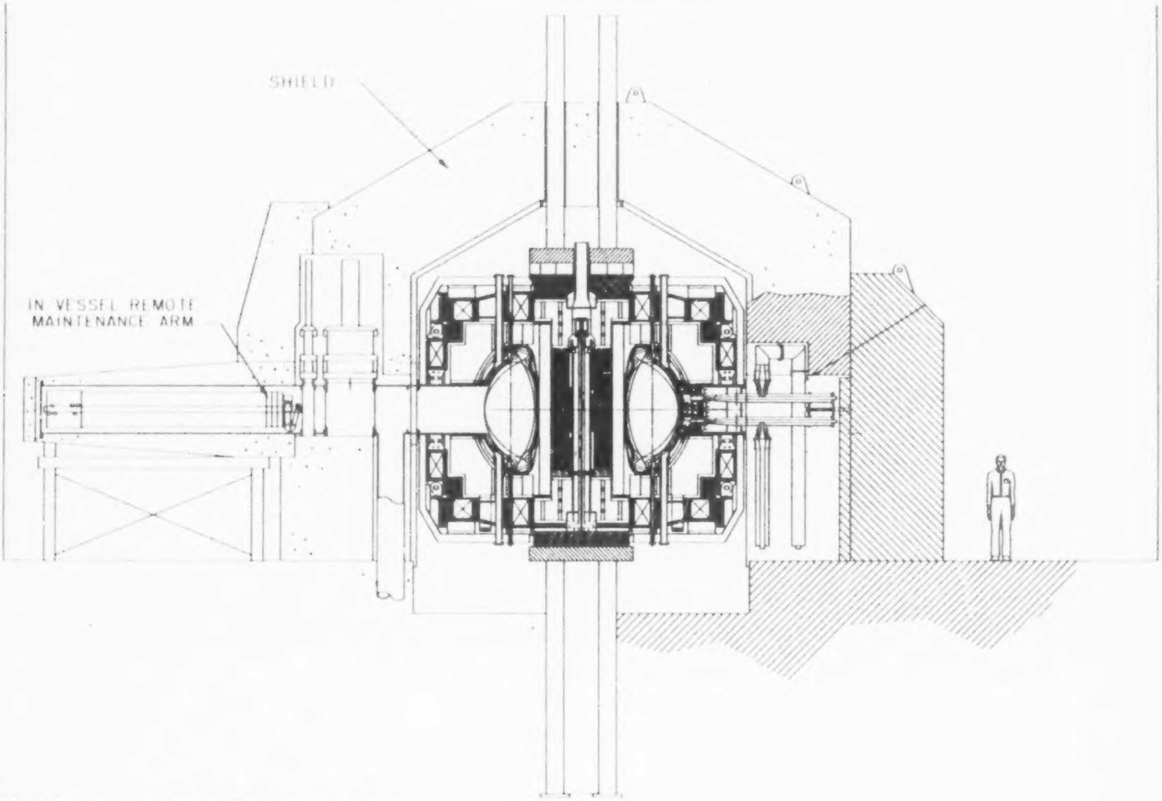
[29] Argonne National Laboratory, *Technical Planning Activity: Final Report*, op. cit., table S.12, p. 44 and table S.16, p. 48.

[30] U.S. Congress, House Committee on Science and Technology, Task Force on Science Policy, *Science Policy Study Background Report No. 4: World Inventory of "Big Science" Research Instruments and Facilities*, Serial DD, prepared by the Congressional Research Service, Library of Congress, 99th Cong., 2d sess., December 1986, pp. 111, 121, and 127.

[31] Argonne National Laboratory, *Technical Planning Activity: Final Report*, op. cit., p. 79.

Figure 4-15.—Preliminary CIT Design



SOURCE: Princeton Plasma Physics Laboratory, 1987

gin in 1993, and annual operating cost is estimated at about $75 million. According to a review by a panel of the Magnetic Fusion Advisory Committee (MFAC)[32], CIT will be able to study most of the effects that generation of alpha particles might have in a fusion plasma.

Ever since TFTR was designed in the mid-1970s, the design for a successor device has been a topic of active interest in the fusion community. As far back as 1977, proposals were made for compact, high-magnetic-field tokamak devices using high-performance copper magnets; this is the approach that was selected for CIT. Other proposals, which were ultimately not adopted, called for long-pulse tokamaks using superconducting magnets and costing well over over $1 billion. The CIT design is intended to focus on scientific aspects of the fusion process, and it will not necessarily form the engineering basis for future fusion reactors: CIT's copper magnets consume amounts of electricity that would be prohibitive for commercial purposes, they cannot operate for longer than a few seconds at a time without overheating, and their compact size does not provide enough room for a blanket to recover fusion energy or breed tritium. But CIT will have the ability to resolve critical physics uncertainties sooner and at lower cost than an experiment having more of the engineering features that a reactor would require. Moreover, although specifics of the CIT design may not be applicable to future reactors, the overall approach of high-field, high-performance magnets in fact may be relevant if such magnets can be made with superconducting technology.

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[32] The Magnetic Fusion Advisory Committee is a committee consisting of scientists and engineers from academia, national laboratories, and industry that advises DOE on technical matters concerning fusion research. An MFAC subpanel (Panel XIV, chaired by Dale Meade of Princeton Plasma Physics Laboratory) reviewed plans for CIT in the *Report on Assessment of Burning-Plasma Phenomena in a Compact Ignition Tokamak*, Feb. 10, 1986. The subpanel's report was reviewed by the full MFAC in *Magnetic Fusion Advisory Committee Report on Compact Ignition Experiments (Charge XIV)*, submitted to Dr. Alvin Trivelpiece, Director, Office of Energy Research, Department of Energy, Washington, DC, February 1986.

CIT is being designed through a national effort with wide-based technical support, and the project has been endorsed by MFAC as a "cost-effective means for resolving the technical issues of ignited tokamak plasmas."[33] MFAC determined that the "existing tokamak data base is adequate, with credible extrapolation, to proceed with the design of the CIT," and that by fiscal year 1988 "we should have acquired sufficient information from present large machines to support proceeding with the construction of the CIT."[34] MFAC also stated that CIT "should be part of a balanced overall fusion program," implying that it should not drain funds away from "other essential elements . . . in the DOE Magnetic Fusion Program Plan."[35]

Long-term burn issues, which cannot be addressed by CIT, will require another device in the future. Even if constructed solely to study physics issues, such a device would probably cost at least $1 billion. If other functions such as nuclear technology testing were incorporated, the cost would be even higher.

Fusion Materials

According to TPA, "the ultimate economics and acceptability of fusion energy, as with most other energy sources, will depend to a large extent on the limitations of materials for the various components."[36] Addressing the specific material issues identified earlier in the chapter requires facilities for testing and evaluating candidate materials. Some of this testing can be done by exposing materials to neutrons in fission reactors. Fission-generated neutrons, however, differ in energy and effects from fusion-generated neutrons; tests of materials in fission reactors have to be carefully arranged in order to provide meaningful data on fusion neutron effects.

Eventually, a high-intensity source of 14-million-electron-volt (14-MeV) neutrons will be required to evaluate the lifetime potential of most materials. To accelerate the effects of aging, the test facility must generate neutron irradiation levels significantly higher than those expected in a reactor. Such levels could be provided by a device such as a driven fusion reactor, which would generate fusion neutrons but consume more power than it generated. Such a device would be completely impractical as an energy source, but could be an effective method of generating high fusion neutron intensity over a small volume (10 to 1,000 cubic centimeters).

TPA estimates that a materials irradiation test facility would cost from $150 million to $250 million and would take about 4 years to build. Materials testing would also require several additional facilities each costing $10 million or less.

Fusion Nuclear Technology

Fusion nuclear technologies are those involved with the recovery of energy from the fusion reaction and the breeding and recovery of tritium needed to replace the tritium consumed in the reaction. Most of the nuclear technology functions of a fusion reactor are incorporated in the first wall, blanket, and shield.

The first wall/blanket test program is currently at a very early stage. However, the characteristics of the required experiments have been defined in the FINESSE study.[37] A number of experiments, each costing about $5 million, will be important for guiding the future of the program. Several larger experiments will be needed to follow up on the earlier ones; each of these will cost up to tens of millions of dollars to build and $1 million or more a year to operate.[38]

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[33] *Magnetic Fusion Advisory Committee Report on Compact Ignition Experiments (Charge XIV)*, letter from MFAC chair Fred L. Ribe to Dr. Alvin Trivelpiece, Director, Office of Energy Research, Department of Energy, Feb. 24, 1986.

[34] Ibid.

[35] Ibid.

[36] Argonne National Laboratory, *Technical Planning Activity: Final Report*, op. cit., p. 259.

[37] The FINESSE study is a 3-year study done for DOE involving organizations and scientists from the United States, Europe, and Japan. The study produced many publications; one example is "A Study of the Issues and Experiments for Fusion Nuclear Technology," by M. A. Abdou, et al., *Fusion Technology* 8, November 1985.

[38] Argonne National Laboratory, *Technical Planning Activity: Final Report*, op. cit., table 4.13, pp. 234-236.

After individual facilities enable blanket concepts and components to be designed and the number of options to be reduced, a large-scale nuclear technology demonstration facility will be required to integrate these components and test them under fusion reactor conditions. Such a large-scale device must not only produce enough fusion power to provide a realistic environment for nuclear technology testing, but it must also incorporate development and construction of the individual nuclear technology systems themselves. If this device is also intended to address the physics issues associated with long-term fusion burns, it will become still more complex and expensive.

One possibility, identified by the FINESSE study and reviewed and adopted by TPA, is building a nuclear technology demonstration facility that does not simultaneously serve as the long-burn physics test facility. A device built solely to study nuclear technologies would need a source of fusion-generated 14-MeV neutrons, but this source would not need to be an ignited plasma. Such a device could test scaled-down versions of nuclear technology components, provided that these results could be applied with confidence to reactor-sized versions. TPA estimated that such a nuclear-technology-only device would cost about $1 billion and would take 5 to 6 years to build. TPA did not estimate operating costs for this device.

TPA identified as a second possibility an engineering test reactor (ETR) that would include both long-term burn physics and nuclear technology studies. Such a device would require an ignited or near-ignited plasma, making it big enough to accommodate full-size nuclear technology components. Both the more stringent physics requirements and the need for full-scale nuclear technology components would make an ETR much more expensive than a nuclear-technology-only facility. TPA estimated the cost to build an ETR at about $3 billion. It did not estimate operating costs but said that the experience with TFTR would suggest $150 million annually.[39]

If a nuclear-technology-only device is built instead of an ETR, an additional device would be required specifically to study long-term burn. This additional experiment would probably cost more than $1 billion. Further expense would come later when the tested nuclear technology systems were scaled to reactor-level and integrated with a reactor-sized plasma. Thus, the cost of an ETR cannot be compared only to the cost of a nuclear technology device plus a long-term burn device.

Although DOE recognizes the need for an ETR or equivalent, it has no plans to build one. The Japanese and European programs each have plans to design such a device independently, but neither has yet committed to its construction. The Soviet and the U.S. fusion programs, on the other hand, appear to prefer international collaboration on such a facility. The U.S. Government has proposed to the other major fusion programs that conceptual design of an international engineering test reactor, called the International Thermonuclear Experimental Reactor (ITER), be jointly undertaken. The U.S. proposal does not extend to multinational construction of such a device. However, at the conclusion of the conceptual design effort, the parties could decide whether they wanted to proceed with construction, either independently or jointly. Possible avenues of future international collaboration in fusion research are discussed in chapter 7.

Resource Requirements

Schedule

TPA identified six major decision points that determine the course and schedule of future fusion research, leading up to the overall assessment of fusion's potential. In figure 4-16, each decision is pegged to a key technical issue and to a year.

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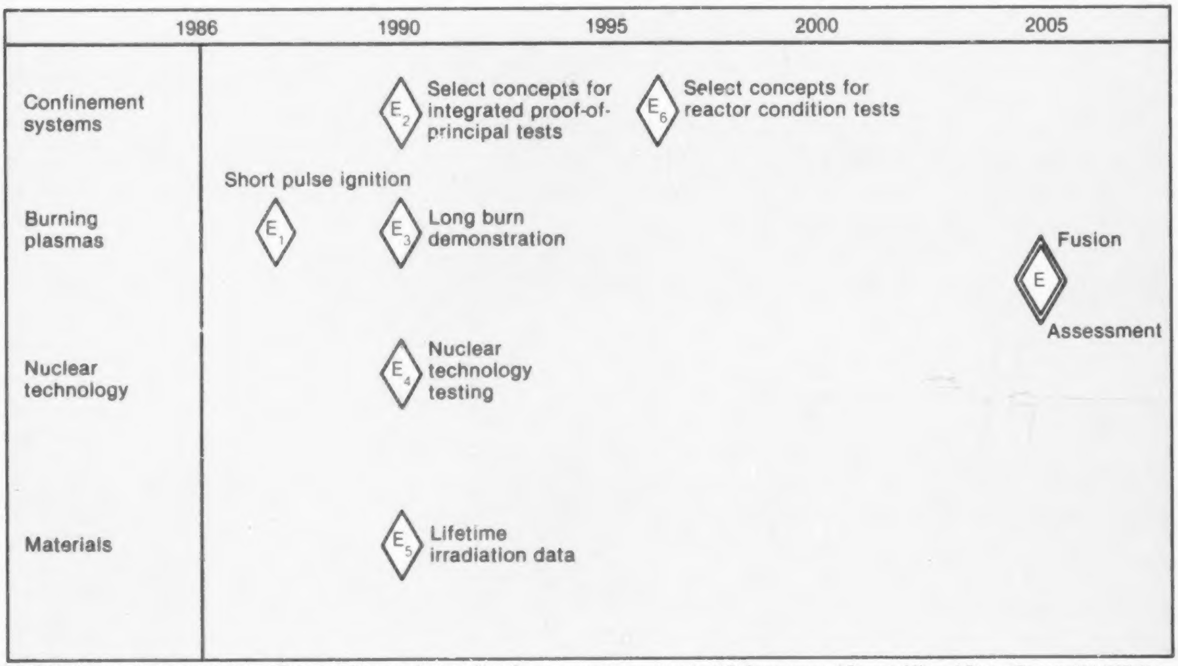
[39] It is not clear how this estimate of $150 million is obtained; it is not computed merely by assuming the annual operating expense of a device to be a specific fraction of its capital cost. Were the estimate made in this manner, it would be considerably higher. The ratio of annual operating expense to capital expense for TFTR is about 15 percent, and that projected for CIT is about the same if the value of existing facilities at Princeton Plasma Physics Laboratory is included in CIT's capital cost. Applying this 15 percent ratio to an engineering test reactor would predict annual operating expenses of close to $500 million.

However, fusion scientists argue that there is no reason to believe the ratio of operating expense to capital expense to be the same for an ETR as it is for significantly smaller devices. They agree that the more a device costs to build, the more it will cost to operate. However, they maintain that there is no reason to expect capital and operating costs to increase at the same rate.

Figure 4-16.—Top Level Decision Points in the Magnetic Fusion Program


1986
1990
1995
2000
2005
Confinement systems
E2
Select concepts for integrated proof-of-principal tests
E6
Select concepts for reactor condition tests
Short pulse ignition
Burning plasmas
E1
E3
Long burn demonstration
Fusion
E
Assessment
Nuclear technology
E4
Nuclear technology testing
Materials
E5
Lifetime irradiation data

SOURCE: Argonne National Laboratory, *Technical Planning Activity: Final Report*, commissioned by the U.S. Department of Energy, Office of Fusion Energy, ANL/FPP 87-1, January 1987, figure S.8, p. 23.

TPA did not examine all the possible scenarios resulting from different timings and outcomes for these decisions but instead adopted a "reference scenario" believed to reflect current DOE planning. The years in figure 4-16 are taken from the reference scenario, which is shown in greater detail in figure 4-17.

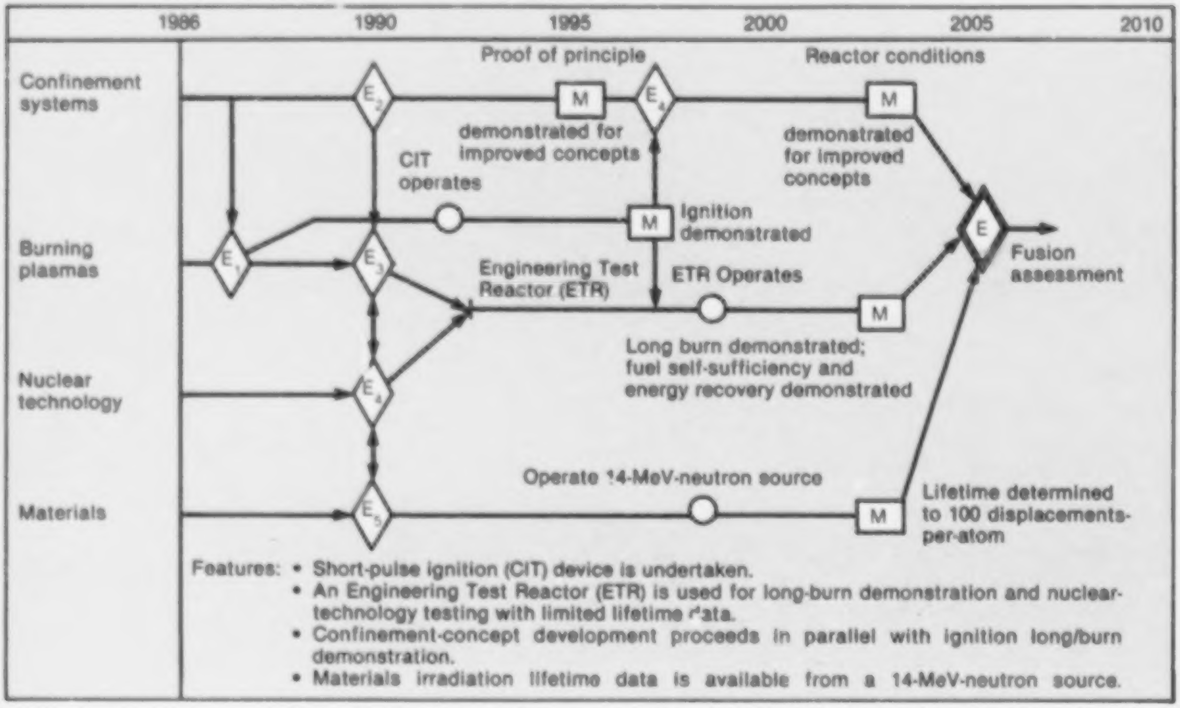
In the reference scenario, the decision to proceed with CIT as the short-term burn experiment is made in 1987. By about 1990, the decision is made to combine nuclear technology studies and long-term burn physics issues in a single engineering test reactor, possibly ITER. At about the same time, decisions are made concerning the nature of a materials testing facility and the selection of confinement concepts to be tested at the proof-of-principle scale. By 1997, certain alternate confinement concepts successfully showing proof-of-principle are selected for reactor-scale demonstration, and the overall assessment of fusion is targeted for 2005. TPA does not conclude that the reference scenario is fastest, cheapest, or most assured of success. Rather, it shows that an exhaustive process of technical review has not uncovered any inconsistencies.

Cost

TPA estimates that the worldwide research required between 1987 and 2005 under the reference scenario will cost in the range of $20 billion. This cost does not include an integrated fusion facility, demonstration reactor, or any other facility constructed after the assessment of fusion in 2005. Total operating cost worldwide is judged to be relatively constant at about $800 million annually, and total yearly funding for fusion research increases to about $1.5 billion in the mid-1990s when construction cost is added. The total construction budget is estimated at about $6 billion, half of which is required for an engineering test reactor.

TPA acknowledges that the ground rules used for cost projection could have been applied more

Figure 4-17.—Reference Scenario for the Magnetic Fusion Program


1986
1990
1995
2000
2005
2010
Confinement systems
Burning plasmas
Nuclear technology
Materials
Proof of principle
Reactor conditions
E_2
M
E_4
M
demonstrated for improved concepts
demonstrated for improved concepts
CIT operates
M
Ignition demonstrated
E_1
E_3
E
Fusion assessment
Engineering Test Reactor (ETR)
ETR Operates
M
Long burn demonstrated; fuel self-sufficiency and energy recovery demonstrated
E_4
Operate 14-MeV-neutron source
E_5
M
Lifetime determined to 100 displacements-per-atom

Features:
- Short-pulse ignition (CIT) device is undertaken.
- An Engineering Test Reactor (ETR) is used for long-burn demonstration and nuclear-technology testing with limited lifetime data.
- Confinement-concept development proceeds in parallel with ignition long/burn demonstration.
- Materials irradiation lifetime data is available from a 14-MeV-neutron source.

SOURCE: Argonne National Laboratory, *Technical Planning Activity: Final Report*, commissioned by the U.S. Department of Energy, Office of Fusion Energy, ANL/FPP-87-1, January 1987, figure S.10, p. 27.

uniformly, that no iterative review of the cost estimates was undertaken, and that no effort was made to estimate the resources required for alternate research scenarios. Nevertheless, the report states that the information gathered is sufficient to present "a broad view of the resources required for a full assessment of the commercial potential of fusion."[40]

Some critics of TPA's cost estimates argue that, since TPA was not charged with designing, managing, and executing an actual research strategy—indeed, TPA was forbidden from performing such programmatic planning, which is strictly DOE's domain—the total cost represents a sum of "wish lists" rather than a realistic budget. According to these critics, without the requirement to conduct the politically difficult task of eliminating research that, although useful, may not be necessary, the estimated total cost is higher than an actual manager would spend when faced with fiscal constraints. Similarly, these critics complain that any study done by experts from a single field has an inherent bias towards overestimating that field's research requirements. Researchers in a field are presumed to have an interest in maintaining or increasing their field's funding, these critics argue, and the researchers would not have any incentive to prepare a study underestimating the cost of research if such a study might be used as justification for cutting the field's research budget.

Other critics, however, feel that any bias in TPA's estimated total is likely to be in the direction of underestimating the total rather than inflating it. Since each technical aspect of the study was analyzed by experts in the field, some degree of technical optimism is probably inherent at each stage; unanticipated difficulties would drive the cost of the research program above TPA's estimates. Moreover, these critics suggest, it would not be in the collective interest of the fusion community to estimate a higher total cost than necessary, since continued support of the fusion program depends on perceptions that its benefits are worth its cost. Overestimating the total cost could threaten the program's support.

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[40] Argonne National Laboratory, *Technical Planning Activity: Final Report*, op. cit., p. 28.

The process by which TPA estimated the total cost of future fusion research involved a wide degree of fusion community participation, and OTA can find no evidence that the estimate is flawed. However, OTA also recognizes that while the researchers in any technical field are the most qualified to estimate costs of experiments in that field, they are also the beneficiaries of support given to the field. Therefore, their estimates may be influenced by non-technical factors, although it is not clear whether the estimate would be too high or too low as a result.

Summary

Probability of Success

It seems likely that at the conclusion of the research program, fusion's technological feasibility—the ability to use fusion power to generate electricity—can be shown. The fusion program has made steady progress over the last 35 years on the key technical issues. It is still possible that fusion's scientific feasibility will be impossible to demonstrate, due to surprises in the behavior of a plasma that generates substantial amounts of fusion power. However, successfully attaining ignition in CIT will resolve most of the scientific uncertainties.

Most of the subsequent scientific and engineering challenges in designing and building a reactor have been identified. **Once scientific feasibility is established, a concerted and well-funded research effort should be able to develop a reactor that produces fusion power. However, it cannot yet be determined whether or not such a fusion reactor will be commercially attractive.** Characteristics and prospects of fusion as a commercial energy source are discussed in chapter 5.

Findings

Estimates of the annual worldwide funding required to evaluate fusion's potential early in the next century are several times today's annual U.S. fusion research budget. The estimated annual worldwide funding is, however, on the order of the amount now spent each year by all the world's major fusion programs put together. The funding estimates suggest three possibilities to U.S. policymakers for continuing the U.S. fusion research program:

1. With funding levels several times their present level and with a significant measure of technical success, the U.S. fusion program can decide on its own whether or not to begin the demonstration and commercialization of fusion power in the early part of the next century.
2. If the major world fusion programs can collaborate and plan their research efforts to complement each other and eliminate duplication, and if the effort has a significant measure of technical success, a collective assessment to proceed with fusion's development could be made early in the 21st century. In this case, only modest increases in funding would be required for each of the world's fusion programs, with the exact amount of the increases depending on how well the programs were able to avoid duplication of research.
3. If major international collaboration is not attained, and if the U.S. fusion budget is not increased to the point where the necessary research can be carried out domestically, the United States cannot assess fusion's potential until later in the next century.

These possibilities form the basis of the policy options discussed in greater detail in chapter 8.

Chapter 5

Fusion as an Energy Program

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Chapter 5

Fusion as an Energy Program

The primary long-term goal of U.S. fusion research is to develop a fusion reactor that is an attractive source of electricity.[1] The overall role that fusion might play in the future energy supply of the United States depends on the characteristics of such a fusion reactor and on the characteristics of other energy technologies with which fusion will compete. It is too early to evaluate either of these characteristics: fusion's commercial prospects are not yet known and neither are the prospects of developments in other technologies. However, preliminary analyses can be performed on the basis of fusion system studies conducted to date.

CHARACTERISTICS OF FUSION ELECTRIC GENERATING STATIONS

Pre-conceptual designs and feasibility studies for fusion generating stations were developed as long ago as 1954.[2] However, it was not until the early 1970s that studies began to simultaneously address the plasma physics, structural materials, operating characteristics, economics, and environmental implications of fusion reactors.[3] During the late 1970s and early 1980s, comprehensive system studies and comparative models were developed to evaluate the interdependence of fusion reactor performance and various scientific and technological parameters.

These studies represent a mix of technological optimism and conservatism. They optimistically assume that the research and development (R&D) effort mapped out in chapter 4 of this assessment will be successfully completed and that it will permit a fusion reactor to be designed and built. At the same time, studies are inherently conservative in that they cannot account for as-yet-unforeseen developments and innovations in fusion and competing technologies.

The studies have been especially valuable in identifying improvements in fusion physics or technology that appear to have the greatest potential for making fusion reactors attractive and competitive. Their value to the fusion program notwithstanding, system studies should not be considered definitive assessments of future fusion reactors. Given that the scientific and technological base for fusion has not yet been established, fusion system studies are inherently based on incomplete information, and the values calculated for reactor parameters such as capital cost and cost-of-electricity must be considered highly uncertain. As a result of the technical progress made in fusion research, system studies today describe reactors that are very different from those envisioned 30 years ago. It is likely that the fusion reactor that eventually enters the marketplace will make today's designs appear just as dated.

The discussion that follows identifies generic features of future fusion reactors as well as factors that depend on particular design choices. The focus is on reactors that produce electricity from fusion alone, called *pure fusion* reactors, as distinguished from fusion reactors that draw part of their energy from fission or that are used to make fissionable fuel.[4] Much of the discussion draws on comparisons of fusion technology to present-generation light-water reactor fission technology, the closest analog to fusion for which significant operational data exists. Fusion and fission plants are comparable because both are nuclear technologies suited for central-station power generation, and because they share some of the same environmental and safety concerns. However, the further that a technology is extrapolated beyond present experience, the less certain any of its features become. As a result, *all* characterizations of future systems—including the ones in this chapter—should be treated with extreme caution.

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[1] Fusion also may be valuable in a number of non-electric applications, described in app. A.

[2] L. Spitzer, Jr., et al., *Problems of the Stellarator as a Useful Power Source*, NYO 6047 (Princeton, NJ: Princeton University, 1954).

[3] The evolution of fusion reactor studies is discussed in *Fusion Reactor Design: On the Road to Commercialization*, by G.L. Kulcinski, Fusion Engineering Program, Nuclear Engineering Department, University of Wisconsin, UWFDM-529, Madison, WI, May 31, 1983, p. 3.

[4] These devices, called *fission/fusion hybrid* reactors, are discussed in app. A.

Risk and Severity of Accident

The D-T fusion process has several advantages over fission that should make it easier to assure the safety of a fusion reactor than of a fission reactor. This statement does not imply that existing fission reactors are unsafe, or that fission technology will not continue to develop and improve. However, assuring public safety with fusion technology should be easier for the following reasons:

- **Fusion reactors cannot sustain runaway reactions**. Fuel will be continuously injected, and the amount contained inside the reactor vessel at any given time would only operate the reactor for a short period (probably seconds or less). A fission reactor, on the other hand, contains several years of fuel in its core—a far greater amount of stored energy potentially available for release. Moreover, the conditions necessary to sustain a fusion reaction are difficult to maintain; any significant system malfunction would stop the reaction.
- **Fusion reactors should require simpler post-shutdown or emergency cooling systems than fission reactors, if such systems are needed at all**. Due to the decay of radioactive materials in the reactor, both fusion and fission reactors will continue to generate heat at a small fraction of the full power rate after they have been shut down. In a fission reactor, this decay heat, or *afterheat*, is largely due to fission byproducts that accumulate in the spent fuel rods. In a fusion reactor, afterheat results mostly from radioactivity induced in the reactor structural materials, and the afterheat level is highly dependent on the choice of those materials. With appropriate materials choices, afterheat from fusion reactors should be much less than from fission reactors.
- **Potential accidents that could occur in fusion reactors should be less serious than those that could take place in fission reactors**. With suitable materials choices, the radioactive inventory of a fusion reactor should be considerably less hazardous than that of a fission reactor. Fusion reactors would not contain biologically active fission products such as strontium and iodine. Moreover, the radioactive materials in a fusion reactor would generally be less likely to be released in an accident than would those in a fission reactor, since they would largely be bound as metallic structural elements. The only volatile or biologically active radioactive component in a fusion reactor would be the active tritium inventory; gaseous and volatile radioactive products in a fission reactor would be present in amounts orders of magnitude greater.

A recent study of fusion's environmental, safety, and economic attributes quantitatively compares the safety of fusion and fission designs.[5] This study, referred to here as the ESECOM report, sorts various fission and fusion reactor designs into four categories according to the means by which prompt off-site fatalities are prevented in the event of an accident. Some of the designs studied depend on active safety systems to prevent off-site fatalities. These reactors can be safe, but demonstrating their safety involves certifying that the safety systems will work as expected during all conceivable accidents. In other designs, and the safety of these systems is much easier to demonstrate.[6]

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[5] John Holdren, et al., *Exploring the Competitive Potential of Magnetic Fusion Energy: The Interaction of Economics With Safety and Environmental Characteristics*, excerpts from the Report of the Senior Committee on Economic, Safety, and Environmental Aspects of Magnetic Fusion Energy (ESECOM). Interim results from this study were presented to the Magnetic Fusion Advisory Committee in Princeton, NJ, on May 19, 1987; the full report should be published as a Lawrence Livermore National Laboratory report in September 1987. This study will be cited hereinafter as the ESECOM report.

ESECOM analyzed and compared the environmental, safety, and economic aspects of eight pure fusion reactor designs, two fission/fusion hybrids, and four types of fission reactor. Of the pure fusion reactors, six were tokamaks and two were reversed-field pinches; both the hybrid reactors were tokamak-based.

The levels of safety assurance derived by ESECOM, ordered by increasing ease of demonstrability, are:

- **Level 4: Active Protection.** This level of protection depends on the proper operation of active safety systems to ensure safety.[7] It is extremely difficult to certify that such systems will indeed work as expected in case of accident. These systems must be designed to respond to particular contingencies, and deciding which accident scenarios should be covered is not easy. Furthermore, as the 1986 Chernobyl accident in the Soviet Union showed, active safety systems can be disconnected. At this level of protection, it is impossible to eliminate the risk of operator error.
- **Level 3: Small-Scale Passive Protection.** At this level, safety does not depend on active safety systems. Moreover, failure of components such as relief valves and pump seals—in conjunction with the failure of any active systems—could be tolerated without risking off-site fatalities. However, ensuring safety at this level requires assuming the integrity of key systems such as coolant loops, as well as maintaining the large-scale physical integrity of the overall structure. It would have to be proven that passive design features alone could keep these critical components or systems from being damaged under credible accident scenarios.
- **Level 2: Large-Scale Passive Protection.** A large-scale passively protected reactor would be able to prevent the release of dangerous amounts of hazardous materials as long as certain large-scale structures remained intact. Such a system would not rely on active safety systems and would be able to withstand any combination of small-scale component or system failures. Demonstrating the safety of such a reactor would only require showing that no credible accident could destroy the large-scale geometry of the device.
- **Level 1: Inherent Safety.** A reactor with this degree of safety assurance could be shown to be incapable of causing an immediate, off-site fatality in the event of any conceivable failure, including total system reconfiguration (e.g., it would remain safe even if the entire reactor were somehow crumpled up into a ball). This level of protection is assured by the properties of the reactor materials in one of two ways: either the radioactive inventory must be so small that, if totally released, it could not constitute a lethal dose to the public, or the inventory must consist of materials that could not be melted, converted into volatile oxides, or otherwise dispersed by the sudden release (in an explosion, fire, or power surge) of all the plant's stored energy.

According to the ESECOM report, attributes of the fusion process show that fusion reactors should be able to achieve greater degrees of safety assurance than fission reactors. Of the eight fusion designs that ESECOM evaluated, one was a Level 1 system, three were Level 2, one was Level 3, and three were Level 4. Design changes were identified for several of the Level 3 or 4 fusion systems that could raise them to Levels 2 or 3, respectively. ESECOM found that present-generation commercial light-water fission reactors are Level 4 systems, and that two "inherently safe" fission reactor designs now under investigation should be capable of reaching Level 3 on this scale.

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[6] The analysis in this study computes "worst-case" radiation exposures to members of the public by calculating the maximum radiation dose deliverable to an individual at the worst possible location at the plant boundary, under weather conditions that keep the radiation from dispersing. Effects that would serve to mitigate the delivered dose, such as buildings, rain, or fallout, were not included (except that the effect of buildings on the wind pattern was included). Absence of prompt fatalities corresponds to limiting the "worst-case" dose to under 200 rems, an amount of radiation exposure generally accepted to be the minimum capable of causing a prompt fatality in the absence of medical treatment. This radiation dose is about 2,000 times the total dosage typically received in one year due to cosmic rays and other naturally occurring sources of radiation.

In addition to prompt radiation dose, the study also considered the long-term dose from ground contamination due to an accident. However, these long-term dosages were not used to define the categories of safety assurance. Long-term effects of radiation release are more difficult to determine than prompt effects because the effects of long-term, low-level exposure to radiation are highly controversial. Estimates of the cancer fatalities resulting from a given long-term, low-level exposure vary by more than a factor of 10.

[7] Under the ESECOM analysis, any system such as an emergency cooling system that would have to be activated or powered at the time of an accident, or any system that would have to be actively turned off, is considered an active system. A containment building is considered an active system under this definition since penetrations such as airlocks, ventilation systems, and plumbing are managed by active systems. Therefore, designs relying significantly on containment buildings to prevent escape of radiation could not achieve a rating higher than Level 4.

Different fusion designs varied significantly in terms of the maximum radiation dose that could be delivered to the public in an accident. Designs using low-activation materials, which do not generate long-lived radioactive byproducts under neutron irradiation, and designs operating on advanced fuel cycles were calculated to have a higher degree of safety assurance than the "reference" design, an updated version of a tokamak reactor study originally published in 1980.[8] However, materials selections and design choices are also possible that yield fusion reactors that require active safety systems.

ESECOM concluded that Level 2 fusion reactors should be possible to design, and that Level 1 designs—although more difficult due to limited materials choices—should also be possible. None of the fission designs ESECOM analyzed could attain these levels of safety assurance. Although fission designs are being developed that appear to have greater degrees of safety assurance than existing fission reactors, fusion appears to have some fundamental advantages. Many of the potentially dangerous substances present in fission reactors are either fuels or fission byproducts that are inherent to the fission reaction. The products of the fusion reaction, on the other hand, are not in themselves hazardous. Tritium fuel does pose a potential hazard, but according to the ESECOM report even the complete release of the active tritium inventory of current reactor designs under adverse meteorological conditions would not produce any prompt fatalities off-site.[9] There is much greater freedom to choose appropriate materials that minimize safety hazards in fusion reactors than in fission reactors. Therefore, a higher degree of safety assurance should be attainable with fusion.

Occupational Safety

Most of the occupational hazards a worker might encounter at a fusion reactor site are already familiar from other occupations. Table 5-1 shows the locations of potential hazards during the operation and maintenance of a D-T fusion reactor.

Of the potential hazards listed, the least is known about the effects of magnetic fields. There is no reason to suppose that the steady or slowly varying magnetic fields associated with fusion reactors could cause adverse health effects. However, little is known definitively about the biological effects of such fields; after many years of research, the technical literature is "extensive and often contradictory."[10] The U.S. Department of Energy (DOE) established interim occupational magnetic field exposure guidelines on an ad hoc basis in 1979, although the committee that developed these guidelines expressed "strong concerns about the lack of data upon which one can construct appropriate exposure criteria."[11]

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[8] Charles C. Baker, et al., *STARFIRE—A Commercial Tokamak Power Plant Study*, ANL/FPP-80-1, Argonne National Laboratory, 1980. The STARFIRE study, conducted by a team of 70 researchers, is one of the most comprehensive fusion reactor design studies completed to date. It presents a conceptual design of a full fusion powerplant, including descriptions of the tokamak reactor as well as all the associated subsystems in the remainder of the facility.

The STARFIRE study has been extensively drawn upon by, and provides a base of comparison for, many subsequent analyses of fusion reactors and system designs. The ESECOM report chose the STARFIRE design, updated with lower activation materials and a more recent blanket design, as its "point-of-departure" reference case.

[9] John Holdren, et al., *ESECOM Report*, op cit. Larger "inactive" tritium supplies would be stored in the plant in addition to the active working inventory, but these could be divided up and extremely well protected.

[10] J.B. Cannon (ed.), *Background Information and Technical Basis for Assessment of Environmental Implications of Magnetic Fusion Energy*, DOE/ER-0170, prepared by the Oak Ridge National Laboratory for the U.S. Department of Energy, Office of Fusion Energy, Division of Development and Technology, August 1983, p. 6-2.

This document, hereinafter referred to as *Background Information*, served as the principal reference for a generic Environmental Impact Statement that was prepared for the magnetic fusion program. The generic statement, although completed, has not been reviewed and approved by DOE. DOE has chosen not to file a generic impact statement for the program as a whole but rather to prepare specific statements for individual fusion facilities as needed.

[11] Letter from Dr. Edward Alpen, Director of the Donner Laboratory, University of California at Berkeley, and Chairman of the committee established to set interim magnetic field exposure standards, to Dr. Kenneth Baker, U.S. Department of Energy, July 23, 1979.

Table 5-1.—Principal Locations of Potential Hazardous Agents in D-T Fusion Reactors

Hazard	Locations of possible exposure during operation[a]	Locations of possible exposure during maintenance
Radiation from tritium	• Tritium recovery systems • Coolant loops	• Reactor hall and structure • Blanket processing • Fuel recycling
Radiation from activation products	• Coolant loops	• Reactor hall and structure • Blanket processing • Steam generator
Radiation from neutrons	• Not present in accessible areas	• Not present
Non-radioactive toxic materials	• Possibly in auxiliary reactor systems	• Chemical processing
Radiofrequency (RF) fields	• Near power sources • Along waveguides	• Not present unless RF components are being tested
Magnetic fields	• Environment of reactor hall	• Not present unless magnets are being tested

[a] Hazards are only listed for areas where personnel will be permitted. Personnel will not be permitted in the reactor hall during reactor operation, so activation products and neutron radiation present there are not considered occupational hazards in this table.

SOURCE: Adapted from J.B. Cannon (ed.), *Background Information and Technical Basis for Assessment of Environmental Implications of Magnetic Fusion Energy*, DOE/ER-0170, prepared by Oak Ridge National Laboratory for the U.S. Department of Energy, Office of Fusion Energy, Division of Development and Technology, August 1983, table 6.1, p. 6-2.

These standards are still being used on a trial basis; although researchers analyzing this issue have flagged uncertainties that call for further research, they have still not found many well-documented studies that show detrimental biological effects of static (non-varying) or slowly varying magnetic fields such as those to be found in fusion reactors. The National Committee on Radiation Protection and Measurement has established a subcommittee on Biological Effects of Magnetic Fields to recommend limits on magnetic field exposure; this subcommittee is in its final stages of document preparation prior to submission to the full committee.[12]

Significant exposure to magnetic fields in or near a fusion reactor probably would be limited to plant workers because magnetic fields extending beyond the site boundary are not expected to be stronger than the earth's field. The interim standards established by DOE were for occupational exposure only, and the committee that developed them stated that it was "not prepared to offer an exposure criteria for general population exposure."[13]

Environmental Effects

Radioactive Waste

The main environmental problem with fusion reactors is expected to be radioactive waste. Although the reaction products of the D-T fusion reaction are not radioactive, the fusion reactor itself—particularly the first wall, blanket, shield, and coils—will be. The first wall will be the most severely affected; the cumulative effects of radiation damage will require that the first wall be replaced every 5 to 10 years and disposed of as radioactive waste.

The type and amount of radioactive waste generated by a fusion reactor is highly dependent on the choice of materials. With appropriate materials, fusion reactors can avoid producing the long-lived, intense, and biologically active wastes inherently produced by fission reactors. According to the ESECOM report, although fusion wastes may have greater volume than fission wastes, they will be of shorter half-life and intensity and should be orders of magnitude less hazardous.[14] The wastes from fusion reactors operating with advanced, non-tritium-based fuel cycles would be even less radioactive than those from D-T fusion reactors.

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[12] Information provided to OTA staff by Dr. Donald Ross, Acting Director, Occupational Safety and Health Division, Office of Operational Safety, U.S. Department of Energy, Apr. 22, 1987; and by Dr. Dennis Mahlum, chairman of the National Committee on Radiation Protection and Measurement Scientific Committee 67 on Biological Effects of Magnetic Fields, Apr. 28, 1987.

[13] Letter from Alpen to Baker, note 11 above.

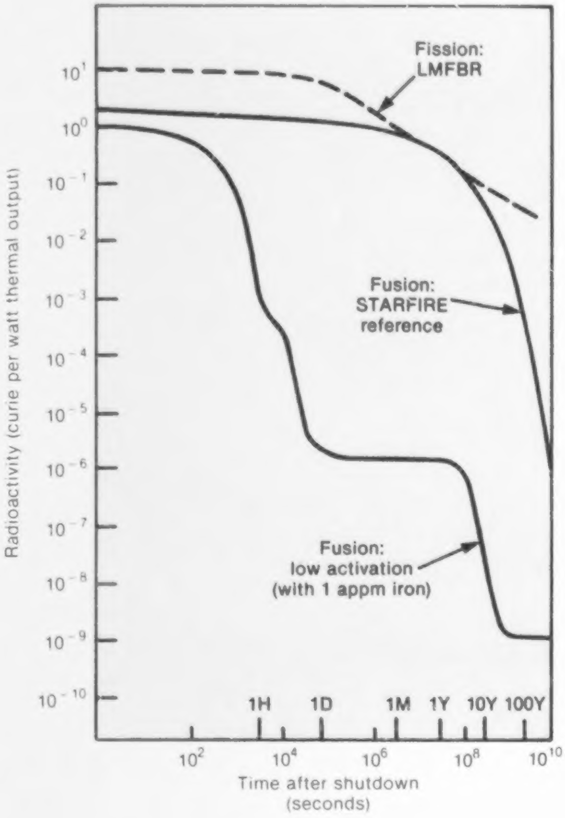
[14] ESECOM measured radioactive waste hazard by calculating the dosages that future "intruders" could acquire by excavating or farming a radioactive waste site hundreds of years from now. Radioactive waste produced by the fusion designs ESECOM studied were orders of magnitude less hazardous than those produced by fission designs by this measure.

ESECOM's estimates of radioactive waste hazards also indicate that fusion designs differ among themselves by several orders of magnitude. The study found that advanced "low-activation" fusion designs could be tens to hundreds of times better than the fusion reference design, and that other designs could be hundreds or thousands of times worse if the wrong materials are chosen. ESECOM concluded that with proper materials selection, radioactive waste from all of the fusion designs could qualify as low-level waste under existing Nuclear Regulatory Commission regulations.[15]

Figure 5-1 shows the dependence of fusion reactor radioactivity levels on materials selection. Figure 5-2 shows the corresponding dependence for afterheat produced by radioactive decay. For the top curve in each figure, the reactor first wall and blanket are assumed to be made out of a type of steel. The lower curve, having radioactivity and afterheat levels thousands to millions of times lower, assumes that low-activation materials are used in the blanket and first wall.[16]

These figures represent the potential of low-activation materials to reduce radioactive wastes but do not necessarily address the feasibility of using these materials. The source for figures 5-1 and 5-2 was a preliminary conceptual design study that attempted to design credible replacements using low-activation ceramic materials for all reactor structures in the high neutron flux zone of the STARFIRE reactor (footnote 8, above). Engineering feasibility of these materials was considered, and at an initial level of analysis the designs were found to be achievable. However, using ceramics for these components poses engineering issues quite different from those encountered with the metals typically used in engineering applications today. Substantial development of materials and fabrication techniques would be required to use ceramics in a fusion reactor.

Figure 5-1.—Post-Shutdown Radioactivity Levels for Fission Breeder Reactor, Reference STARFIRE Fusion Reactor, and Low-Activation Fusion Reactor Design



KEY: H = hour
D = day
M = month
Y = year
appm = atomic parts per million (impurity atoms per million atoms of substrate)
LMFBR = Liquid Metal Fast Breeder Reactor

SOURCE: General Atomic Co., *Low Activation Materials Design Study: Annual Report for Fiscal Year 1981*, GA-A16426, UC-20cd, September 1981, p. 5-4.

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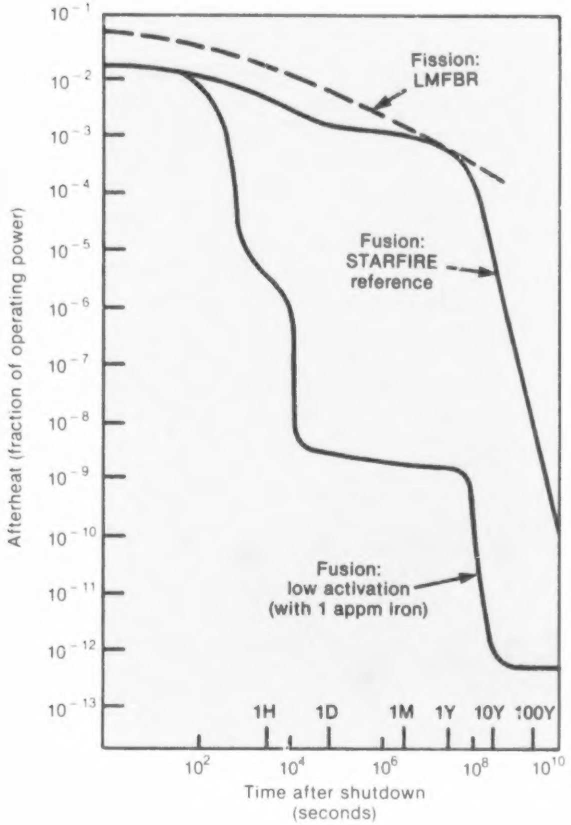
[15] John Holdren, et al., *ESECOM Report*, op. cit.

[16] The induced radioactivity intrinsic to the low-activation materials themselves is extremely small; the majority of the radioactivity shown by the "low-activation" curve more than one day after shutdown is due to iron impurities. According to Cannon, *Background Information*, op. cit., p. 3-41, realizing impurity levels as low as those assumed in this figure is a "difficult and expensive task at the present time, and may or may not be achievable at the time low-activation/low-impurity structural materials are required in a fusion reactor economy."

Figure 5-2.—Post-Shutdown Afterheat Levels for Fission Breeder Reactor, Reference STARFIRE Fusion Reactor, and Low-Activation Fusion Reactor Design



KEY: H = hour
D = day
M = month
Y = year
appm = atomic parts per million (impurity atoms per million atoms of substrate)
LMFBR = Liquid Metal Fast Breeder Reactor

SOURCE: General Atomic Co., *Low Activation Materials Design Study: Annual Report for Fiscal Year 1981*, GA-A16426, UC-20cd, September 1981, p. 5-4.

Routine Radioactive Emissions

The total estimated radiation dosages attributable to routine releases from fusion reactors would be a very small fraction of the radiation dose due to naturally occurring background radiation.[17] Two types of radioactive substances may be emitted by fusion reactors: activation products, which are substances made radioactive by neutron irradiation, and tritium, which is produced in the reactor blanket and used as fuel. Activation products would be released either through liquid waste processing systems or plant ventilation systems; most of the tritium releases would be to the atmosphere.

Activation products released by fusion reactors should be no more hazardous than those routinely released by fission reactors. Tritium discharges from fusion reactors, in terms of radioactivity levels, would be much larger than activation product emissions. However, since tritium differs significantly from activation products in the type of radiation emitted and the method of absorption in the body, the total radiation dosages due to tritium releases would not be correspondingly large.

Very preliminary estimates of tritium emissions from fusion reactors are on the order of 5,000 to 10,000 curies per year from a 1,000-megawatt plant.[18] Most of these emissions would occur during major system maintenance, and they might be removable by an atmospheric detritiation system before release to the environment. Tritium releases of this amount are well within the range of routine tritium releases from some existing DOE facilities. By comparison, tritium emissions from an equivalently sized pressurized-water fission reactor—the predominant type of commercial nuclear fission reactor—would be about

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[17] Naturally occurring background radiation is due primarily to cosmic rays and to radioactive elements contained in rocks and soils. In the United States, the dosages due to these sources vary by factors of 2 to 4 depending on location; the typical contributions of the two sources are comparable.

Medical X-rays and radiopharmaceuticals provide, on average, a radiation dosage about equal to the natural background. A substantially smaller contribution comes from the sum of other manmade sources such as atmospheric nuclear weapons tests, occupational radiation exposure, nuclear powerplant emissions, and consumer products.

[18] One curie of a radioactive substance is the amount needed to have 3.7 × 10^{10} radioactive disintegrations per second. Ten thousand curies of tritium have a mass of about one gram.

1,400 curies per year.[19] It is estimated that the total dose to the population within 80 kilometers (50 miles) of a routinely operating fusion reactor should be less than 0.01 percent of the dose from natural background sources.[20]

Routine Nonradioactive Emissions

The energy generated in a fusion reactor that is not converted into electricity would be discharged as heat, primarily into the atmosphere. In this respect, a fusion reactor would resemble fossil fuel and nuclear fission generating stations. Like a fission plant, but unlike a plant that burns fossil fuels, a fusion plant would *not* emit combustion products such as carbon dioxide into the atmosphere. Since carbon dioxide emissions may potentially affect world climate, this aspect of fusion (and fission) technology could prove to be very advantageous. Carbon dioxide emissions are discussed later in this chapter under "Comparisons of Long-Term Electricity Generating Technologies."

Nuclear Proliferation Potential

A fusion reactor's ability to breed fissionable materials such as uranium or plutonium could possibly increase the risk of nuclear weapons proliferation. A pure fusion reactor would not contain fissionable materials usable in nuclear weapons, and it would be impossible to produce such materials by manipulating the reactor's normal fuel cycle. Therefore, normal operation of a pure fusion reactor poses negligible proliferation risk.[21] However, if the blanket of a pure fusion reactor were appropriately modified, fissionable fuel could be bred there. To ensure that fissionable materials were not surreptitiously produced, changes to the reactor blanket would have to be prevented. The difficulty of detecting such changes would depend on the design of the reactor; it is plausible that reactor designs could be developed that would make undesirable modifications easy (or difficult) to monitor.[22]

Proliferation concerns are not unique to fusion reactors; fission reactors also pose this risk. Depending on the fuel cycle used, the proliferation potential of fission can be much greater than that of a pure fusion reactor. After being irradiated in the core of a fission reactor, uranium fuel will be converted into plutonium, which can be extracted from the uranium and other byproducts by chemical reprocessing. Alternatively, plutonium can be produced in breeder reactors (pure fission or fission/fusion hybrid) designed explicitly for plutonium production. If either reprocessing or breeder reactors become used on a wide scale, it is possible that material usable for nuclear weapons could be produced and extracted during the production, processing, and transportation of fissionable fuel.[23]

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[19] Fusion reactor radioactive discharge and radiation dosage estimates are from Cannon, *Background Information*, op. cit., chs. 4 and 8, particularly tables 4.19, 8.8, and 8.9. Pressurized water reactor emissions are from Nuclear Regulatory Commission, *Calculation of Releases of Radioactive Materials in Gaseous and Liquid Effluents From Pressurized Water Reactors*, NUREG-0017, Rev. 1, 1985, p. 2-70.

[20] Dosages estimated from tritium releases assume that all the tritium is in the form of tritium oxide, or tritiated water. Tritiated water is water in which one or both of the hydrogen atoms are replaced by tritium atoms, and it is absorbed by and discharged from the human body like ordinary water. These dosages represent conservative upper bounds, and are tens of thousands of times higher than the dosages that would result if the tritium were released in the form of tritium gas. Tritium gas is not readily absorbed by the body.

[21] Pure fusion reactors do contain tritium, which could be used in thermonuclear weapons such as the hydrogen bomb. However, such weapons cannot be built by parties who do not already possess fission weapons, and possession of tritium will not provide any assistance to a party that is trying to develop fission weapons.

[22] A fission/fusion hybrid reactor would incorporate a blanket designed specifically to breed (and/or utilize) fissionable fuel. Proliferation concerns for hybrids are therefore considerably more serious than those for pure fusion reactors.

[23] The plutonium produced in a fission reactor consists of a mixture of different isotopes whose relative proportions depend on how long the original uranium is irradiated. Any mixture of plutonium isotopes can be used to make a nuclear explosive, but weapons designers prefer to minimize the percentage of the heavier isotopes that are produced when the fuel is irradiated for longer periods of time. Therefore, short fueling cycles are preferable—but not required—for producing plutonium usable in nuclear weapons. Since plutonium can be produced in this manner in existing fission reactors, the International Atomic Energy Agency operates a safeguards program to assure that production and diversion of fissionable fuel would be detected, minimizing the possibility of covert production of nuclear weapons.

Resource Supplies

Much of fusion's allure stems from the essentially unlimited supply of fuel. D-T fusion reactors will require two elements—deuterium and lithium—for fueling. Deuterium will be used as fuel directly in the reaction chamber and lithium will be used in the blanket to breed tritium fuel. Advanced fuel cycles discussed in chapter 4 that do not use tritium would not require lithium.

It appears that domestic supplies of fusion fuel will not constrain the development and use of fusion power. Deuterium contained in water is readily extractable, with each gallon of water having the energy equivalent of 300 gallons of gasoline. This supply offers billions of years' worth of energy at present consumption rates. Similarly, domestic lithium supplies probably offer thousands of years' worth of fuel with vastly greater quantities of lithium contained in the oceans. Although recovering lithium from seawater is not currently economical, it could be in the future; fuel costs are such a small part of the cost of fusion power that lithium could become many times more expensive without substantially affecting the cost of fusion electricity. According to a study of fuel resources for fusion, it appears "unlikely that an absolute shortage of lithium could constrain the prospects of D-T fusion in any time of practical interest."[24]

Preliminary studies of the materials required to build fusion reactors also do not foresee any important materials constraints, although the preliminary nature of fusion reactor designs makes firm conclusions impossible. In 1983, Oak Ridge National Laboratory conducted a study that estimated a "per reactor" materials demand from a set of fusion reactor design studies completed in the 1970s. These estimates were converted into annual fusion demands by assuming that in the long run, close to 40 fusion reactors would be built per year.[25]

The study compared these estimates to non-fusion demand projections, based on U.S. Bureau of Mines estimates, which were extrapolated over a time span comparable to that assumed for the fusion estimates. The study also compared demand estimates to estimated world supplies.

The study did not find any materials for which total fusion demands exceeded non-fusion demands. Therefore, in those cases for which total demand appeared to exceed available supply when projected over many decades, overall scarcity would not be due solely to fusion. There would be ample motivation other than fusion for either identifying substitutes or finding new sources of supply.[26]

At this stage of fusion reactor design, substitutes can be found for any of the materials that might be in short supply. However, replacing several materials simultaneously, such as all those that would be in short supply if foreign sources were not available, would be much more difficult than finding substitutes for any one material. **If resource constraints affect fusion reactors, they will concern materials for reactor construction rather than fuel supply**.

Cost

Estimating the costs of fusion reactors that cannot yet be designed in detail is difficult. The task is considerably complicated by the fact that economic projections, more than many other features discussed so far, depend critically on parameters that can be little more than guessed at today. Many non-technical factors such as interest rates, construction time, and the licensing and regulatory process will have a profound and unpredictable impact on ultimate cost.

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[24] W. Hafele, J.F. Holdren, and G.L. Kulcinski, "The Problem of Fuel Resources," *Fusion and Fast Breeder Reactors* (Laxenburg, Austria: International Institute for Applied Systems Analysis, 1977), p. 32.

[25] Cannon, *Background Information*, op. cit., ch. 9. The study assumed a worldwide installed electric generating capacity of 1,500 gigawatts, or about 2.4 times the 1986 U.S. installed capacity [given by the North American Electric Reliability Council, "1986 Electricity Supply and Demand," figure 8, p. 25]. Assuming this capacity to be supplied by generating stations averaging 1 gigawatt each and having an average lifetime of 40 years, an average of $1,500 \div 40 = 37.5$ plants would have to be replaced per year. The study assumed that all replacements would eventually be made with fusion reactors.

[26] Ibid., table 9.24, p. 9-36. Although fusion materials demand did not constitute the majority of the total (fusion plus non-fusion) demand for any of the materials studied, fusion requirements constituted between 10 and 50 percent of the total demand for five materials: beryllium, lithium, helium, tungsten, and vanadium. All of these except tungsten were found to be in ample supply.

Fusion demands were calculated from an ensemble of 10 different reactor designs. Such an ensemble represented a diversity of reactor concepts, and using the ensemble kept the analysis from being too dependent on a single design. Any individual reactor design, however, may have materials requirements significantly different from the ensemble average.

Fusion will be a capital-intensive technology. Existing system studies show that most of the cost of electricity will come from building the powerplant. Costs for the deuterium and lithium required to fuel fusion reactors will be a negligible fraction of the total cost. More significant as an effective "fuel" cost will be the expense of periodically replacing the blanket components as they exceed their service lifetimes. Even including these replacements, however, total operational and maintenance expense is projected to constitute less than half of the total cost of fusion-generated electricity.[27]

In analyzing how the costs of fusion electricity depend on various physics and technology parameters, system designers can determine important cost drivers and identify high-payoff areas for further research. Because of overall uncertainties, however, the actual costs estimated in system studies are less dependable than their variation as design assumptions are changed. A National Research Council report on fission/fusion hybrid reactors[28] identifies many sources of uncertainty in present cost estimates, including:

- incomplete design information;
- limited understanding of the required fusion technologies, methods of fabrication, materials, and support systems, including in particular incomplete knowledge of the effects of high-energy neutron irradiation;
- complex requirements for tritium recovery and handling, and the need for remote handling and storage of large, radioactive components;
- the degree of containment facility that will be required for the reactor and for associated tritium handling systems;
- the approach taken towards licensing, including the need for in-service inspection, seismic qualification, redundancy and diversity;
- the costs of waste disposal and decommissioning; and
- the life expectancies and failure modes of plant components, which depend on the combined effects of neutron irradiation, magnetic fields, high temperatures, and corrosion.

Existing information on the costs of fusion experimental facilities does not necessarily provide much guidance for estimating the future costs of commercial reactors. No experiment to date comes close to integrating the various systems that would be required in an operating reactor. Many individuals argue that the proposed costs of future experimental facilities—an engineering test reactor, for example, which will cost at least $1 billion and very possibly several times that much—do not bode well for inexpensive powerplants. However, experimental facilities and commercial devices have very different missions and design constraints.

A number of factors would tend to make commercial facilities less expensive than experimental devices that produce comparable amounts of power. Experiments are necessarily based on incomplete knowledge—otherwise there would be no need for them—and their designs must be conservative to ensure that their objectives can be fulfilled. Experiments must be flexible; they must have the ability to operate under a wide range of conditions, since the operating parameters that will be of most interest for future commercial reactors are not yet known. They must be extensively instrumented with diagnostic equipment, since their primary objective would be to produce information, not electricity. The result of this information and the experience with the technology acquired through the research program should make it possible to reduce the cost of subsequent facilities, including commercial ones.

On the other hand, a different set of factors would tend to increase the cost of commercial facilities over that of their experimental counterparts. Expenses may be incurred in ensuring long life, reliability, ease of maintenance, and ease of operation, qualities that are crucial for commercial facilities but that may not be so important for experimental devices. Many of the design features and requirements introduced in the process of licensing, optimizing, and commercializing fusion reactors will also tend to add to the expense of commercial facilities. It is therefore very difficult to draw conclusions about reactor cost from existing experience or from the cost of proposed experiments.

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[27] J. Sheffield, et al., *Cost Assessment of a Generic Magnetic Fusion Reactor*, Oak Ridge National Laboratory, ORNL/TM-9311, March 1986, table 1.2, p. 7.

[28] National Research Council, *Outlook for the Fusion Hybrid and Tritium-Breeding Fusion Reactors* (Washington, DC: National Academy Press, 1987), p. 90.

ESECOM has conducted the most extensive analysis to date comparing costs of various fusion designs to one another and to fission reactors. In the ESECOM report, construction cost estimates varied by about a factor of 2 among the fusion designs, and the pure fission costs were similar to or below the low fusion estimates. "Cost-of-electricity" estimates varied over a somewhat smaller range, and the fission designs again were at the low end.

The lowest operating cost of any of the reactors examined by ESECOM was for the "best experience" light-water reactor, representing the lowest cost fission reactors now operating. The highest operating cost of all designs was for the "median experience" light-water reactor, representing a cross-section of present light-water reactor experience. Estimated operating costs for all the fusion designs fell in between these cases. Construction cost (as opposed to operating cost) estimates varied similarly, with some of the pure fusion design construction costs exceeding that of the "median experience" light-water reactor.

One feature of fusion reactor design that could significantly affect economics is its level of safety assurance. The easier it is to demonstrate the safety of a fusion reactor, the easier that reactor will be to license and site. In particular, if the licensing process does not depend on complex and controversial calculations concerning the performance of active safety systems, it might proceed more quickly and with greater consensus. If in turn the construction process were sped up, considerable cost savings could result.

Higher degrees of safety assurance could also have a more direct effect in reducing construction cost. Because safe operation of commercial nuclear reactors today depends on active safety systems, those systems must meet exacting quality assurance standards. Components and systems built to meet these "nuclear-grade" standards are considerably more expensive than similar components in less critical applications. Since the safety of reactor designs with higher levels of safety assurance would not be as dependent on particular components or systems, fewer "nuclear-grade" components would be required. The ESECOM report estimated that up to 30 percent of the "overnight" construction costs (e.g., the total cost if construction could be completed instantaneously, not including interest charges or inflation) could be avoided if nuclear-grade construction were not required. Such a decrease in construction cost would lower the cost of electricity by about 25 percent. This savings is overestimated in that no fusion system is likely to be able to avoid nuclear-grade construction entirely; tritium-handling systems, for example, will always have the potential to release some radioactivity in the event of sufficient component failures. Nevertheless, the ability to relax construction standards through higher levels of safety assurance could lead to cost savings.

Possibly mitigating these cost savings is the price of achieving increased safety assurance in the first place. In the ESECOM report, the costs of the pure fusion designs (before any savings due to safety assurance were taken into account) tended to be higher for those designs with higher levels of safety assurance. The net effect of safety assurance on reactor cost, therefore, depends on whether savings can outweigh the price of additional design constraints.

Future technological developments could also decrease the cost of fusion power. For example, the recent discovery of new superconducting materials that do not require liquid helium temperatures could affect fusion design and economics if these materials can be used in fusion magnets. Cheaper magnets, by themselves, will not dramatically alter the price of a fusion reactor. Even if the magnets in the STARFIRE design were free, the total capital cost would only be reduced by about 12 percent.[29] However, if new magnet capabilities in turn make possible the use of significantly different designs—e.g., the use of substantially higher magnetic fields, which could ease the requirements on other systems or permit the use of advanced fuels—then significantly different economic estimates might result.[30]

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[29] J. Sheffield, et al., *Cost Assessment of a Generic Magnetic Fusion Reactor*, op. cit., tables A.4.1 and A.4.2, pp. 84-85.

If reactors running on advanced fuel cycles were developed that had substantially lower levels of neutron irradiation, blanket components would not have to be changed as often, reducing operating costs. However, in the case of the D-^{3}He cycle, the costs of the actual fuel would no longer be negligible due to the expense of generating or recovering ^{3}He, which is not found in nature. Capital cost for the fusion core of a reactor using advanced fuels might be higher than that of a D-T reactor since the advanced reactor technology would be considerably more challenging. On the other hand, if an advanced reactor were able to generate electricity directly, without the use of steam generators and turbines, it might be able to bypass some of the balance-of-plant costs.

Given all the uncertainties, OTA finds that the economic evidence to date concerning fusion's cost-effectiveness is inconclusive. No factors yet identified in the fusion research program conclusively demonstrate that fusion will be either much more or much less expensive than possible competitors, including nuclear fission. Fusion appears to have the potential to be economically competitive, but making reliable cost comparisons will require additional technical research and a better understanding of non-technical factors, such as ease of licensing and construction, that can have a profound influence on the bottom line.

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[30] Possible applications of high field superconducting magnets to fusion reactor design are discussed in *Tokamak Reactor Concepts Using High Temperature, High Field Superconductors*, by D.R. Cohn, et al., Massachusetts Institute of Technology Plasma Fusion Center, PFC/RR-87-5, Apr. 14, 1987.

THE SUPPLY OF AND DEMAND FOR FUSION POWER

The factors that influence how successfully fusion technology will serve as a source of energy include how well fusion's characteristics meet the requirements of potential customers and how well fusion compares to alternate electricity-generating technologies. How well fusion will meet the needs of its users, primarily electric utilities, depends in turn both on when it can become commercially available and on what its users want. These issues are discussed first below. Next is a brief summary of competing energy supply technologies that provides some context for fusion power. Finally, the implications of estimates of future electricity demand are analyzed.

The Availability of Fusion Power

Financial resources permitting, the research program outlined by the Technical Planning Activity (TPA)[31] and described in chapter 4 is targeted toward enabling a decision on fusion's overall potential to be made by 2005. According to TPA, if the decision is made to proceed with fusion at that time, an "Integrated Fusion Facility" (IFF) based on "commercially relevant fusion technology" could be built that would mark the "beginning of the commercialization phase of fusion."[32] TPA did not specify the nature of the IFF. It could be a demonstration or prototype reactor, although the IFF parameters TPA presented in an example show it to be well short of commercial performance (see ch. 4, footnote 28). Thus, the technical steps that might follow the research phase, in terms of the necessary facilities that would lead to a prototype commercial fusion reactor, have not yet been determined.

The institutional process by which any demonstration fusion reactor might be built and operated is also highly uncertain. Under present Federal policy, building and operating a demonstration reactor is the responsibility of the private sector, which has certainly proven capable of demonstrating major new technologies in the past. However, involving the private sector in an effort of this scale may not be straightforward. According to one utility executive:

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[31] The Technical Planning Activity was a fusion communitywide effort to identify the technical issues, tasks, and milestones that characterize the remaining fusion research effort. Its primary output was *Technical Planning Activity: Final Report*, prepared by the Argonne National Laboratory, Fusion Power Program, for the U.S. Department of Energy, Office of Energy Research, ANL/FPP-87-1, January 1987. The Technical Planning Activity is described in the section of ch. 4 titled "The Technical Planning Activity."

[32] *Technical Planning Activity: Final Report*, op. cit., pp. 9 and 26.

> . . . there is a certain level of concern for the enormous gap in perception that exists between industry and government concerning private sector commercialization. It may be unrealistic to assume that once a scientific and related technology data base is established in the program, the stage will be set for private sector commercialization of attractive fusion energy sources.[33]

Unless the Federal Government becomes responsible for owning and operating fusion generating stations—a change whose ramifications would extend far beyond fusion's development—some mechanism for easing the transition from government to private responsibility will be required.[34]

The timing of the commercialization process is difficult to predict for both technical and institutional reasons. Conceivably, if the research program provides the information necessary to design and build a reactor prototype, such a device could be started early in the next century. After several years of construction and several more years of qualification and operation, a base of operating experience could be acquired that would be sufficient for the design and construction of subsequent reactors. If the regulatory and licensing processes proceeded concurrently, vendors could begin to consider the manufacture and sale, and utilities could consider the purchase, of commercial fusion reactors midway through the first half of the next century.

The subsequent penetration of fusion reactors into the energy market would take time because existing electrical generating capacity will not be replaced overnight. If early fusion plants can be built and operated without undue delays or surprises, they may begin to develop a satisfactory track record that will stimulate further construction; if early plants show unfavorable operating experience, commercialization will be delayed. At any rate, it will take decades from their first successful demonstration for fusion reactors to generate a considerable fraction of the Nation's electricity. **Even under the most favorable circumstances it does not appear likely that fusion will be able to satisfy a significant fraction of the Nation's electricity demand before the middle of the 21st century.**

The Desirability of Fusion Power

Ultimately, fusion's commercial potential will be determined by its ability to meet societal needs more effectively than its alternatives. This determination will be made by the eventual purchasers of fusion technology, most likely electric utilities. However, given the long-term nature of the fusion program, it is difficult to predict what characteristics will be important to future customers. The best that can be done is to identify those attributes that are important to utilities today, recognizing that utilities and their requirements may evolve with time.

Certainly one of the most important factors will be the capital cost of fusion plants and the cost of fusion-generated electricity. Although fusion may be economically competitive with other energy technologies, it is not likely to be substantially less expensive. Nevertheless, without a demonstrable economic advantage, it might be difficult to convince potential purchasers to risk substantial investments in what would be an unknown and unproven technology.

Even if fusion cannot beat its competitors economically, it still may be judged preferable on environmental, safety, and resource security grounds. If the potential of fusion technology in these areas is achieved, and if these attributes are important enough to compensate for an economic penalty, explicit policy decisions could be made to promote fusion through legislation or regulation. Barring such direct intervention, however, the primary determinant of fusion's market penetration probably will be cost.

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[33] Kenneth L. Matson, Vice President, PSE&G [Public Service Electric & Gas Co.] Research Corp., Newark, NJ; quoted in "Panel Discussion on Industry and Utility Perspectives on Future Directions in Fusion Energy Development," *Journal of Fusion Energy*, vol. 5, No. 2, June 1986, pp. 144-145. This issue of the *Journal of Fusion Energy* presents an edited transcript of a symposium sponsored by Fusion Power Associates titled "The Search for Attractive Fusion Concepts."

[34] For more discussion of the role of the private sector in fusion's development, see the section in ch. 6 on "Private Industry."

In addition to purely economic factors, a number of additional factors—most of them indirectly influencing the cost of energy—are also important to present utilities. The Electric Power Research Institute (EPRI) surveyed a number of electric utilities in 1981 to determine how important factors other than the cost of energy would be to their acceptance of fusion. The results of the survey are shown in table 5-2.

EPRI found that utilities identified four factors as "vital" and ten as "very important" for future fusion reactors. Although it is too early to evaluate how well fusion will be able to satisfy these requirements, the potential of the technology in some areas can be noted. For example, successfully designing fusion reactors with high levels of safety assurance could satisfy *plant safety* requirements, lessen *financial liability*[35], and improve *plant licensability*. In addition, if fusion reactors could be convincingly demonstrated to be safe, *siting flexibility* might be increased; reactors could be located close to population centers on sites that would not be considered for fission reactors.

Table 5-2.—Utility Requirements Summary (in addition to cost of energy)

Requirement	Weighting
A. Utility planning and finance	
1. Plant capital cost	Vital
2. Plant O&M[a] and fuel cost	Important
3. Outage rates	Very important
4. Plant life	Important
5. Plant construction time	Very important
6. Financial liability	Vital
7. Unit rating	Moderately important
B. Safety, siting, and licensing	
1. Plant safety	Vital
2. Flexibility of siting	Very important
3. Waste handling and disposal	Very important
4. Decommissioning	Important
5. Licensability	Vital
6. Weapons proliferation	Important
C. Utility operations	
1. Plant operating requirements	Very important
2. Plant maintenance requirements	Very important
3. Electrical performance	Very important
4. Capability for load change	Moderately important
5. Part load efficiency	Moderately important
6. Minimum load	Moderately important
7. Startup power requirements	Important
D. Manufacturing and resources	
1. Hardware materials availability	Very important
2. Industrial base	Very important
3. Fuel and fertile material availability	Very important

Order of significance
1. Vital
2. Very important
3. Important
4. Moderately important

No factors were judged "slightly important"; factors judged "unimportant" have been deleted from the list.)

[a]Operations and maintenance

SOURCE: Electric Power Research Institute, *Utility Requirements for Fusion*, EPRI AP-2254, February 1982, table 2-1, p. 2-3.

Potential advantages for fusion reactors also emerge with respect to other utility requirements. Due to its virtually limitless fuel supply, fusion should be able to satisfy the *fuel availability* criteria. Moreover, it appears that the *waste handling and disposal* should be better addressed by fusion than by fission.

A number of uncertainties remain for other factors of importance to utilities. At present, there is virtually no *industrial base* for fusion, although existing fission, aerospace, and materials industries all have capabilities relevant to fusion's needs. Developing fusion's industrial base is essential if the commercialization process is to succeed. Moreover, due to uncertainties in economic studies, how well fusion will be able to minimize *plant capital cost* cannot yet be determined. In addition to affecting the cost of energy through life-cycle capital amortization, large capital expenditures can complicate corporate financial management in areas such as debt-to-equity ratios and capital flexibility. It is clear that fusion reactors will be capital-intensive, but at this stage of development their costs cannot be accurately determined.

Hardware availability, which measures the cost, scarcity, and supply dependability of materials required for plant construction, cannot be determined at this stage of design. Factors such as *outage rates, plant construction times, plant operating requirements, plant maintenance requirements*, and *electrical performance*, also viewed as very important by utilities, probably cannot be evaluated until fusion reactors are well into the commercialization process. Experience with construction, operation, and maintenance of the reactors will be necessary to fully understand these aspects of fusion technology.

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[35] Financial liability measures the maximum potential financial losses due to death, injury, property damage, loss of revenue, and other costs in the event of an accident.

A factor that is interesting due to its relatively low weighting is *unit rating*, or the electrical capacity of a particular generating station. In the early 1970s, fusion reactor conceptual designs had electrical outputs considerably higher than those of existing generating stations. Subsequent designs have lowered electrical capacities to 1,000 megawatts of electricity or less, more in line with existing stations; some recent studies have even considered fusion plants generating as little as 300 megawatts of electricity, although at a higher projected cost of electricity.[36] Now that fusion reactor designs are sized within the range of utility experience—together with the relative unimportance of this parameter —fusion reactors should have little trouble meeting unit rating requirements.

Comparisons of Long-Term Electricity Generating Technologies

This section summarizes the long-range potential of various electricity generating technologies in the 21st century and discusses possible problems associated with their use and/or further development. A detailed examination of the characteristics of these energy technologies, however, is beyond the scope of this report.[37]

The role of demand modification, such as conservation and improvement in the efficiency of energy use, is critical in determining future energy requirements. However, as shown in the following section on "Fusion's Energy Context," the level of electricity demand does not strongly affect the relative demand for fusion power compared to its alternatives. Therefore, improved efficiency of energy use is not specifically discussed here as a generating technology.

Fossil Fuel Technologies

Coal.—Coal is the most abundant energy source in the United States and is currently used to generate over half of the Nation's electricity.[38] According to the Energy Research Advisory Board:

> Coal supply for the 1985-2020 period does not seem to require any special attention at this time . . . It has been the conventional wisdom that the U.S. coal resource base is of such magnitude that it can be safely relied upon to supply any demand for the foreseeable future. This would be true even if nuclear generation does not grow and if a major demand for coal-based synthetics should arise.[39]

Many coal technologies are highly developed and well understood, and they are economically attractive. Proven domestic reserves of coal are adequate to maintain present rates of use for several hundred years. However, there are serious environmental impacts associated with or anticipated from the combustion of coal. Mitigating these adverse environmental impacts increases the cost of coal combustion and may reduce the efficiency of conversion to electricity. Furthermore, coal combustion inherently produces carbon dioxide gas, which may affect world climate and make the use of coal undesirable.

The main near-term problem associated with the use of coal appears to be emissions of combustion byproducts such as sulfur and nitrogen oxides and particulates. These emissions are a major contributing factor to acid deposition, also called "acid rain." Air pollution from coal and other fossil fuel combustion can harm natural ecosystems, damage economically important materials, impair visibility, and may affect human health.[40]

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[36] One study presenting cost of electricity as a function of electrical output is J. Sheffield, et al., *Cost Assessment of a Generic Magnetic Fusion Reactor*, op. cit., figure 4.17, p. 48.

[37] Selected OTA studies that have examined other energy technologies in more detail include *New Electric Power Technologies: Problems and Prospects for the 1990s*, OTA-E-246 (Washington, DC: U.S. Government Printing Office, July 1985); *Nuclear Power in an Age of Uncertainty*, OTA-E-216 (Washington, DC: U.S. Government Printing Office, February 1984); and *Industrial and Commercial Cogeneration*, OTA-E-192 (Springfield, VA: National Technical Information Service, February 1983).

[38] In 1985, coal generated 1,401 billion of the 2,469 billion kilowatt-hours of electricity generated in the United States, according to *Annual Energy Review 1985*, published by the U.S. Department of Energy, Energy Information Administration, DOE/EIA-0384(85), table 81, p. 185.

[39] Energy Research Advisory Board, "Appendix D: Coal Research and Development," by Eric H. Reichl, *Guidelines for DOE Long Term Civilian Research and Development*, vol. VI, Report of ERAB Supply Subpanel, Long-Range Energy Research and Development Strategy Study, A Report of the Energy Research Advisory Board to the U.S. Department of Energy, DOE/S-9944, December 1985, p. 65.

The near-term environmental problems associated with coal and fossil fuel combustion, though serious, can be controlled. The release of combustion byproducts can be mitigated by using cleaner fuels, attaining more complete combustion, or cleaning ("scrubbing") the combustion exhaust. Several technologies to reduce undesirable combustion byproducts are currently available, and more are being developed.[41] Such pollution abatement systems make coal-fired electricity somewhat more expensive, but they do not eliminate coal as a major source of future electricity supply. With the exception of carbon dioxide buildup, discussed below, issues concerning the environmental acceptability of coal combustion are resolvable by burning cleaner fuels or by using "clean coal" technologies.

Oil and Gas.—Oil and gas today generate substantially less electricity in the United States than coal.[42] The domestic resource bases for oil and gas are considerably smaller than coal's, and for this reason oil and gas technologies are not generally included in discussions of long-range electricity supply over the periods in which fusion may make a major contribution.

In the nearer term, however, these fuels—particularly gas—may have an increasing role in electricity generation and may very well form part of the mix of generating technologies at the time that fusion reactors are first introduced. Advanced gas turbines now under development may be highly efficient sources of electricity emitting far less combustion byproducts than current coal plants. Furthermore, such turbines would produce only about one-third as much carbon dioxide per kilowatt-hour as a coal generation plant, reducing (but not eliminating) carbon dioxide emissions as well.[43] Near-term electricity generating technologies are discussed in a separate OTA assessment.[44]

Carbon Dioxide Buildup.—Carbon dioxide (CO_2) is formed as a byproduct of the combustion of fossil fuels—coal, oil, and gas. In the past several decades, the amount of CO_2 in the atmosphere has increased about 10 percent, largely as a result of fossil fuel combustion. Atmospheric carbon dioxide gas can trap some of the heat radiated from the earth instead of allowing it to escape into space. Therefore, the buildup of CO_2 is associated with a global warming effect, sometimes called the "greenhouse effect."

Increased use of fossil fuels is only one potential contributor to global warming. Other gases released into the atmosphere, such as methane, nitrous oxide, and chlorofluorocarbons, have similar heat-retaining properties and may, in aggregate, contribute as much as CO_2 to global warming. Moreover, the connection between fossil fuel use and global warming is influenced by factors such as the production and use of CO_2 by green plants, its absorption by the oceans, and vegetative decomposition. Global warming is potentially a very serious problem, and the consensus within the scientific community studying the issue is that such a warming appears inevitable if emission of CO_2 and other "greenhouse gases" continues to increase. However, there is no certainty to date about the timing and magnitude of the effect, nor about what its climatic implications might be.

The use of fossil fuels will always produce CO_2; there is no way to eliminate CO_2 as a product of the combustion process. As noted above, however, different fossil fuels and combustion technologies produce different amounts of CO_2 per unit of generated energy. Techniques to capture the CO_2 from fossil fuel combustion emissions have been proposed, but they are generally considered to be impractical for either economic or technological reasons. Neither is there a practical way to recover CO_2 and other greenhouse gases that are already in the atmosphere. The only way to reduce CO_2 emissions from fossil fuel combustion is to curtail the combustion of fossil fuels.

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[40] U.S. Congress, Office of Technology Assessment, *Acid Rain and Transported Air Pollutants: Implications for Public Policy*, OTA-O-204 (Washington, DC: U.S. Government Printing Office, June 1984), pp. 9-13.

[41] Ibid., Appendix A.2: "Control Technologies for Reducing Sulfur and Nitrogen Oxide Emissions," p. 152.

[42] Total use of oil and gas, however, including uses other than electricity generation, is greater than that of coal.

[43] Part of the reduction is due to the higher efficiency of these turbines; part is due to the lower carbon content of the fuel.

[44] *New Electric Power Technologies: Problems and Prospects for the 1990s*, op. cit., chs. 4 and 5.

Limiting the use of fossil fuels will not be easy. The simplest way, up to a point, would be to increase the efficiency of energy use, lessening the growth of energy demand. Displacing fossil fuel usage with other energy technologies will be more difficult. Coal will continue to be a major source of electricity for the early 21st century, and deemphasizing its use would foreclose a substantial resource base. Oil and gas currently generate more CO_2 annually than coal due to their heavier use; much of their use is in decentralized applications such as transportation and space heating where they will be difficult and expensive to replace.

Without government intervention, technologies developed to reduce fossil fuel usage must be economically preferable to succeed. Because CO_2 buildup would be a global problem, fossil fuel combustion would have to be reduced on a global scale. It is not clear that developing nations would be willing or able to shift from fossil fuels to other energy sources if doing so would impose serious economic hardship. Furthermore, those regions of the world that might benefit from CO_2-induced climatic change would have no incentive to reduce CO_2 emissions unless they were otherwise compensated.

Possible global warming due to carbon dioxide buildup is a complex problem with a number of contributing causes. It provides an incentive to develop new technologies that can substitute for or otherwise curtail the use of fossil fuels. However, the degree to which these new technologies reduce fossil fuel use will depend heavily on their economic advantages, and any reductions they contribute to fossil fuel use will occur gradually.

Nuclear Fission Technologies

Nuclear fission currently appears to be the main alternative to the widespread future use of coal. The technology is well developed and relatively well understood, and it is supported by a substantial research and development infrastructure. In 1985, 95 nuclear powerplants produced 16 percent of U.S. electricity supply,[45] and nuclear power is likely to remain the second largest source of domestic electricity generation (after coal) into the 21st century. Nuclear fission may become a more important source of electricity if CO_2 or other environmental problems require constraint of coal combustion. The main impediments to increased use of nuclear fission appear to be its unfavorable economics and concern about health and safety. In the long run, many decades from now, fuel constraints may affect the potential of nuclear fission unless more efficient technology, fuel reprocessing, or fuel breeding is instituted.

Public Acceptance.—The long-term feasibility of nuclear fission technologies will require resolution of health and safety concerns. Nuclear power is currently the target of widespread opposition for several reasons. Members of the public feel that mechanisms to dispose of radioactive wastes are inadequate to prevent the ultimate release of dangerous radioactive effluents. Moreover, there is concern about the safety of nuclear reactors, particularly in the aftermath of the Three Mile Island (U.S.) and Chernobyl (U.S.S.R.) accidents. The potential for mechanical failure and operator error casts doubt on the integrity of reactor safety systems.

Economics.—The economics of nuclear power are currently uncertain for several reasons, not all of which are related to characteristics of the technology. The technology is complex and demands strict quality control; nuclear plant construction requires longer lead times and greater capital investment than coal plants. Changing regulations, inadequate management at some plants, and time-consuming litigation add to its cost. The combination of these factors with the soaring interest rates of the late 1970s resulted in costs much higher than expected. Although some plants—even in recent years—have been built on schedule and within budget, the more common experience has been so traumatic that utilities will continue to be extremely cautious about undertaking new nuclear construction. Furthermore, large-scale plants—the only type available at present for nuclear fission—are unattractive in the situation of uncertain demand growth that utilities now face. Smaller scale, modular plants that track load growth more flexibly are preferred in these circumstances.

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[45] *Annual Energy Review 1985*, op. cit., pp. 185, 205.

Fuel.—The light-water reactor technology currently used in fission reactors is capable of extracting only a small fraction of the energy potentially available from uranium fuel rods. In the "once-through" fuel cycle currently in use, the fuel rods are withdrawn from the reactor and stored or disposed of once they become unusable. With greatly expanded use of fission reactors of this type, the demand for uranium would increase and the supply of inexpensive uranium would eventually be depleted. At some point, the price of uranium would rise high enough to make light-water reactor technology economically prohibitive, although current projections indicate that such a point is not likely to be reached before the middle of the next century. Advanced convertor reactors, which extract much more energy from the uranium fuel, are being developed and could extend uranium supply still further.

If the price of uranium rises too high for even advanced convertor reactors to be economical on a once-through fuel cycle, other fuel cycles may be possible. These fuel cycles are sufficient to give fission technology a very long-term resource base. However, since these cycles involve the production, separation, and transportation of fissionable fuel, they could increase the risk of nuclear proliferation over that of a once-through fission economy. (See the discussion of "Nuclear Proliferation Potential" earlier in this chapter).

Research and Development.—It does not appear that nuclear fission technology is unusable or necessarily uneconomical. Extensive research is currently directed at developing advanced fission reactors that will be more acceptable to the public and more attractive to utilities; the intent of this research is to demonstrate that future nuclear fission reactors with very different characteristics than current plants can be a viable source of electricity. In particular, the nuclear industry is attempting to develop passively safe reactors that could not release large amounts of radioactivity due to operator error or mechanical malfunction.[46] Research and development are also focusing on making modular reactor systems, which could be constructed with shorter lead-times and less financial risk to the utilities, and on developing systems that use fuel more efficiently.

The nuclear industry appears to have the potential to develop a superior advanced reactor, and a number of designs for such powerplants exist. However, it is less certain that public confidence in the nuclear industry will improve significantly, particularly in the near term. Without restoring public confidence, the long-term nuclear option may be unattainable.

Renewable Energy Technologies

In addition to coal-fired and nuclear fission powerplants, there are several renewable energy technologies. Two well-developed renewable technologies currently contribute significantly to world energy supply: hydroelectric power and conventional biomass (wood), although only the former is used significantly to generate electricity. Several other technologies, such as wind, unconventional biofuels, solar photovoltaics, geothermal, solar thermal, and ocean energy, may offer significant contributions during the 21st century.[47]

Renewable energy sources are attractive because many of them do not require construction of large facilities for optimal economic operation and because their fuel supplies are continually replenished. Other attractive features of some, but not all, of these technologies, according to an OTA report, "include fewer siting and regulatory barriers, reduced environmental impact, and increased fuel flexibility and diversity."[48]

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[46] Such designs have been called "inherently safe." However, inherent safety in this sense differs from the usage adopted by the ESECOM report and discussed earlier in this chapter in the section on "Risk and Severity of Accident" under "Characteristics of Fusion Electric Generating Stations." The ESECOM report found that passively safe fission reactors—although having greater safety assurance than existing nuclear plants—would not attain the highest levels of safety assurance, including the level ESECOM labeled "inherent safety."

[47] Energy Research Advisory Board, "Appendix D," op. cit., p. 11.

[48] *New Electric Power Technologies*, op. cit., p. 19.

Problems associated with renewable energy sources, however, may limit their role as major sources of electricity. Few of the technologies are currently economically competitive in other than highly specialized applications. Many renewable resources are only available intermittently, and their availability depends on factors like the weather and the time of day. Moreover, the availability of renewable technologies depends on geography and climate. The average amount of available solar energy varies significantly across the United States, largely as a result of differing weather conditions. Wind energy is most effectively recovered in California and Hawaii. Finally, most renewable energy sources are diffuse, requiring central-station powerplants to occupy more land than those using technologies such as coal and fission. On the other hand, the diffuse nature of renewables also makes them well-suited for decentralized applications, which may offset the need for large centralized facilities.

In general, both technical and economic improvements are needed to make renewable energy technologies competitive in the 21st century. Research is being conducted on a wide variety of approaches for harnessing these energy sources, and significant improvements are likely. Nevertheless, it is not expected that renewable technologies will eliminate the need for central-station generating technologies such as coal and nuclear fission.

Nuclear Fusion Technology

Unlike the other supply options, nuclear fusion is still in a pre-development stage. Much of the technology required for generating electricity from magnetic fusion has not been demonstrated, and the commercial potential of fusion cannot yet be determined.

Nuclear fusion appears to have attractive features. First, it could have significant environmental advantages with respect to other central-station generating technologies. The fusion process does not produce CO_2, nor—with appropriate choice of materials—does it appear that radioactive waste will be as high-level or as biologically hazardous as waste produced by nuclear fission. Second, it appears possible to design fusion reactors that will not depend on active safety systems to prevent serious accidents; such reactors could have a higher degree of safety assurance than fission reactors. Finally, high levels of safety assurance, environmental advantages, and independence from geographical constraints could make siting a nuclear fusion powerplant considerably easier than siting a plant based on another energy technology.

The ultimate feasibility of nuclear fusion will not be known until the technology is developed and can be compared with the other energy options that exist at that time. At this point, it is only possible to make projections based on the characteristics of the technology and the research necessary to overcome problems identified to date.

Table 5-3 compares various future electricity supply options, based on extrapolations of current technologies. On this basis, magnetic fusion has the potential to be a very attractive energy source. Obviously, unanticipated developments in any of the technologies described in this table could significantly alter their future role.

Fusion's Energy Context

The anticipated need for energy over the period in which fusion would undergo commercialization will influence the urgency of fusion research and the pace of its entry into the energy supply marketplace. OTA convened a workshop in November 1986 to examine the factors that would determine demand for electricity in general and fusion in particular. Several points became clear during the discussion:[49]

- **The overall size and composition of electricity demand, by itself, should neither require nor eliminate fusion as a supply option**. Economics and acceptability, rather than total demand, will determine the mix of energy technologies. If fusion technology is preferable to its alternatives, it will be used

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[49] Fusion Energy Context Workshop, Office of Technology Assessment, Washington, DC, Nov. 20, 1986. A list of participants is given at the front of this report.

Table 5-3.—Comparison of Prospective Long-Range Electricity Supply Options

Energy source	Advantages	Disadvantages and research needs
Coal	• Plentiful • Technology exists today • Safe	• Near-term environmental implications require development of "clean coal technologies" or fuel substitutions that may increase the cost of energy • CO_2 buildup may make increased dependence on fossil fuels undesirable
Oil and gas	• Technology exists today • Fewer combustion byproducts emitted than coal • Less CO_2 emitted per unit energy than coal	• Questionable long-term resource base • Does not avoid CO_2 emission
Fission	• Plentiful • No emission of CO_2 • No emission of combustion byproducts • Technology exists today	• Unfavorable economics and safety concerns suggest development of advanced reactor designs that are smaller and passively safe • Nuclear waste disposal not yet resolved • Public confidence must be improved and may or may not result from technical improvements
Renewables	• Unlimited fuel supply • No net CO_2 emission • Technologically simple • Modular design	• Uncertain economics and technical problems require more R&D • Intermittency and diffuseness may make renewables inadequate substitute for central-station power generation in arbitrary locations
Fusion	• Unlimited fuel supply • Potential for higher degree of safety assurance than fission • No CO_2 production or combustion byproduct emission • Substantially less hazardous nuclear waste than fission	• Significant R&D effort required to establish technical feasibility • Environmental and safety potential highly dependent on design, especially on materials choice • Economic potential unknown

SOURCE: Office of Technology Assessment, 1987

to replace retired generating capacity even if overall demand is low. If fusion proves inferior to its competitors, it may not be used even at very high demand levels. Fuel supplies for both coal and nuclear fission are adequate to meet high levels of demand for at least a few hundred years without fusion. However, late in the next century, fission may require the use of breeder reactors.

Should fusion technology prove favorable, rapid growth in demand would facilitate its introduction because the opportunities for new powerplant construction would be greater. Nevertheless, demand alone cannot turn an unattractive technology into an attractive one.

- **It is unlikely that any one technology will take over the electricity supply market, barring major difficulties with the others**. At present, a number of supply technologies have roughly equivalent marginal costs of production, and all participate in the supply mix.
- **Given that technologies such as coal combustion and nuclear fission are already commercialized, fusion will have to prove better—not only comparable—before it can start to displace them**. The criteria on which fusion will be judged include economic, safety and environmental issues as well as resource security. Advantages in one area may, but will not necessarily, compensate for shortcomings in another.
- **Potential problems with the major technologies currently viewed as supplying electricity in the future provide incentives to develop alternate energy technologies and/or substantially improve the efficiency of energy use**. Considerable expansion of coal use may prove undesirable due to the "greenhouse effect"; safety or proliferation concerns may similarly impair expansion of the nuclear fission option. Over the long run, fusion could provide a substitute for these technologies. The urgency for developing fusion, therefore, depends on assumptions of

the likelihood that existing energy technologies will prove undesirable in the future.

- **There is little to be gained and a great deal to be lost if fusion is prematurely introduced without attaining its potential economic, environmental, and safety capabilities**. Even in a situation where problems with other energy technologies urgently call for development of an alternative source of supply, that alternative must be preferable in order to be accepted. It would be unwise to emphasize one fusion feature—economics or safety or environmental advantages—over the others before we know which aspect will be most important for fusion's eventual acceptance.
- **New energy technologies take a long time to develop and gain wide use**. It currently appears that it will be many decades before fusion will be able to supply a significant fraction of U.S. electricity even under optimistic assumptions concerning its technological development.

With respect to global energy demand, in particular, as a motivation for fusion, workshop participants discussed various estimates of future energy demand. Models attempting to chart the evolution of global energy demand over many decades have been developed in the last few years. Because the time periods of interest are much too long for projections of recent experience to be valid, these models must instead simulate the future world economy and use of energy. These models start with a number of assumptions concerning world economic and population growth; the relationship between economic growth, technological development, and energy use; and the resource bases and costs of various energy technologies. The models calculate the evolution of those parameters assumed to be determinants of energy use and then determine desired outputs such as the supply and price of various types of energy.

These models are most useful for parametric analysis: What might be the consequences of some set of actions? Which parameters appear to be the most sensitive determinants of future demand? The models are, however, much less able to project future behavior in any absolute sense. They are inherently simplified, and even if they accurately reflect the behavior of the system they represent, the input data they act on are in many cases highly uncertain.

A recent review of a number of world energy models discusses their respective methodologies and compares some of their results, finding that there is more than an order of magnitude variation in their respective estimates for energy demand in the year 2050 (figure 5-3).[50] The variation results largely from differing input assumptions, as is shown by the fact that, for several of the models, a number of different projections are plotted based on different assumptions or different sets of input data. Nevertheless, unless it is known which assumptions are correct, even a model known to be valid cannot produce valid predictions.

The relative contributions of different forms of energy supply are no better determined than the total energy demands calculated by these models. The costs of different supply technologies cannot be known over the periods of interest and must be assumed. The mix of supply technologies computed by these models therefore depends primarily on the corresponding input assumptions. Furthermore, a detailed sensitivity analysis using one global energy model shows that overall energy consumption figures appear to be much more sensitive to parameters relating to demand—e.g., relative rates of economic development and productivity growth—than to parameters describing supply technologies and costs.[51]

This finding further reinforces the conclusion that predictions of future energy use provide little information about the demand for any particular supply technology. **The urgency for developing fusion technology, therefore, depends on one's assumptions as to the likelihood that existing sources of energy supply cannot be counted on in the future. Little justification can be provided from demand estimates alone**.

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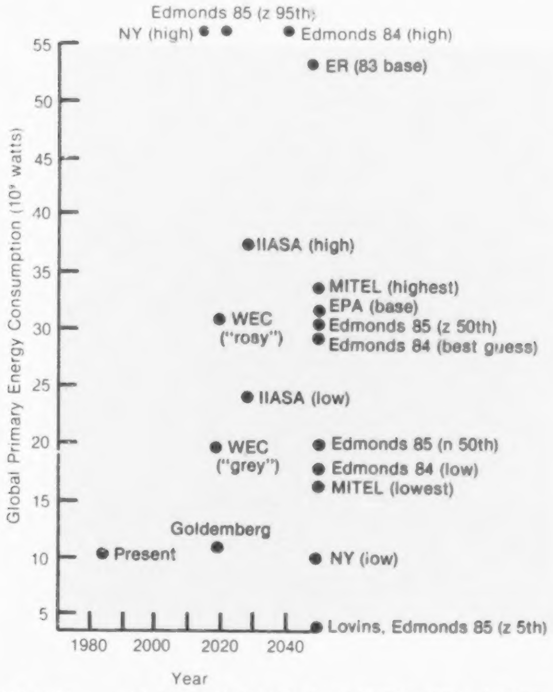
[50] Bill Keepin, "Review of Global Energy and Carbon Dioxide Projections," *Annual Review of Energy*, Jack Hollander, Harvey Brooks, and David Sternlight (eds.), vol. 11 (Palo Alto, CA: Annual Reviews Inc., 1986), p. 357.

[51] J.M. Reilly, J.A. Edmonds, R.H. Gardner, and A.L. Brenkert, "Uncertainty Analysis of the IEA/ORAU CO_2 Emissions Model," *Energy Journal*, vol. 8, No. 3, July 1987, pp. 1-30.

Figure 5-3.—Projections of Global Primary Energy Consumption to 2050



KEY: IIASA: International Institute for Applied Systems Analysis. *Energy in a Finite World: A Global Systems Analysis* (Cambridge, MA: Ballinger, 1981).

Lovins: Lovins, A.B., Lovins, L.H., Krause, F., and Bach, W., *Least Cost Energy: Solving the CO_2 Problem* (Andover, MA: Brick House, 1982).

WEC: World Energy Conference, *Energy 2000-2020: World Prospects and Regions Stresses*, J.R. Frisch (ed.), World Energy Conference Conservation Commission (London: Graham & Trotman, 1983).

NY: Nordhaus, W.D., and Yohe, G., "Future Paths of Energy and Carbon Dioxide Emissions, *Changing Climate* (Washington, DC: National Academy of Sciences, 1983).

MITEL: Rose, D.J., Miller, M.M., and Agnew, C., *Global Energy Futures and CO_2-Induced Climate Change*, MITEL 83-015 (Cambridge, MA: MIT Energy Laboratory, 1983).

EPA: U.S. Environmental Protection Agency, *Warning: Can We Delay a Greenhouse Warming?* S. Seidel and D. Keyes (eds.) (Washington, DC: U.S. Environmental Protection Agency, 1983).

ER: Edmonds, J., and Reilly, J., "Global Energy and CO_2 to the Year 2050," *Energy Journal* 4(3):21-27, 1983.

Edmonds 84: Edmonds, J., Reilly, J., Trabalka, J.R., and Reichle, D.E., *An Analysis of Possible Future Atmospheric Retention of Fossil Fuel CO_2*, Report No. DOE/OR/21400-1 (Washington, DC: U.S. Department of Energy, 1984).

Edmonds 85: Edmonds, J., Reilly, J., Gardner, R., and Brenkert, A., *Uncertainty in Carbon Emissions, 1975-2075*, Report of the Carbon Dioxide Emissions Project (Oak Ridge, TN: Institute for Energy Analysis, 1985).

Goldemberg: Goldemberg, J., Johansson, T.B., Reddy, A.K.N., and Williams, R.H., "An End-Use Oriented Global Energy Strategy," *Annual Review of Energy*, Jack Hollander, Harvey Brooks, and David Sternlight (eds.), vol. 10 (Palo Alto, CA: Annual Reviews Inc., 1985), pp. 613-88.

SOURCE: Bill Keepin, "Review of Global Energy and Carbon Dioxide Projections," *Annual Review of Energy*, vol. 11, 1986, figure 2, p. 364. Data points are keyed to different models analyzed in that paper.

CONCLUSIONS

Characteristics of Fusion Reactors

Fusion reactors appear to have the potential, using only passive systems, to assure safe operation and shutdown in the event of accident, malfunction, or operator error. If this potential for a high degree of safety assurance is realized, a fusion reactor would be easier to certify as safe than a reactor that depends on active safety systems, such as today's fission reactors. Moreover, fusion reactors do not appear likely to pose new types of occupational hazards.

With proper choice of materials, the environmental characteristics of fusion reactors would likely be preferable to other energy technologies. Unlike fossil fuel combustion, fusion does not produce carbon dioxide that could contribute to overall global warming. Fusion reactors will produce radioactive waste, but these wastes should be less radioactive, less hazardous, and easier to dispose of than those from nuclear fission reactors. However, fusion reactor designs can differ by orders of magnitude in the amount of radioactive waste to be generated. In principle, waste generation can be greatly minimized by the use of materials that would not generate long-lived radioactive isotopes inside a fusion reactor; such materials must still be developed and tested. Routine radioactive emissions from fusion reactors are expected to be insignificant.

One of the most attractive features of fusion is its essentially unlimited fuel supply. Sufficient deuterium is available and recoverable at low cost from water to provide energy for billions of years at present rates of use. The lithium needed to breed tritium in D-T reactors is not as plentiful as deuterium, but it is nevertheless present in sufficient quantity that supply of adequately priced fuel is very unlikely to constrain the prospects of D-T fusion over any time of conceivable interest. Pending detailed fusion reactor designs, other resource requirements are harder to estimate, however, there is no reason to believe that other resource requirements will constrain fusion's development.

Projections of the economics of fusion reactors are inconclusive at this stage of fusion's development. Existing studies tend to show the cost of electricity from present fusion designs would be somewhat more expensive than that of existing energy supplies. However, these studies cannot be considered definitive for a number of reasons. First, any comparisons between prospective technologies and existing ones are highly uncertain, considering the disparate levels of development. Second, fusion's costs are difficult to estimate because substantial research and development remains to be done. Technical features that may lead to decreased fusion costs are being explored, and the ultimate success of these features is uncertain. Alternatively, technical problems that drive up the cost may be encountered. More significantly, fusion's economics will be profoundly affected by non-technical factors— e.g., the ease and length of the construction and licensing processes—whose impact on fusion costs is not well understood at present. Finally, the costs for fusion's potential competitors are uncertain.

Timetable for Fusion Power

Considering the remaining technical research to be done and the time period needed for the commercialization process to result in substantial market penetration, it does not appear likely that fusion will be able to satisfy a significant fraction of the Nation's electricity demand before the middle of the 21st century. The degree to which fusion is indeed able to penetrate the energy market depends on how effectively it meets the needs of its customers in comparison with other energy technologies. Although the needs of 21st century utilities cannot be predicted with confidence, a number of features desirable to utilities today can be identified. Economic competitiveness is certainly one of the most important; other crucially important attributes are plant capital cost, safety, licensability, and maximum financial liability in case of accident. Developing fusion reactors with high degrees of safety assurance would make fusion attractive in many of these respects.

Competitors with fusion have the potential to supply most or all of the electricity required by the United States in the first half of the next century; the overall size of future electricity demand should neither require nor eliminate fusion as a supply option. However, there are potentially fundamental problems involving the alternate suppliers of electricity that could make fusion the technology of choice. The degree to which fusion will replace its competitors is impossible to predict today.

Chapter 6

Fusion as a Research Program

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Chapter 6

Fusion as a Research Program

The ultimate objective of fusion research is to produce a commercially viable energy source. Yet, because the research program is exploring new realms of science and technology, it also provides a wealth of near-term, non-energy benefits. A complete analysis of the fusion energy program must include the immediate, indirect benefits and costs of the ongoing research effort, in addition to its progress in reaching its long-term goal.

NEAR-TERM BENEFITS

Fusion research has provided four major near-term, non-energy benefits. It has been a driving force behind the development of plasma physics. It educates plasma physicists who contribute to fusion and other fields. It produces technologies with valuable applications elsewhere, and it has put the United States in a strong position in the world scientific community.

Development of Plasma Physics

The development of the field of plasma physics was driven by the needs of scientists working on controlled thermonuclear fusion and space science and exploration. In the case of fusion energy,

> The simultaneous achievement of high temperatures, densities, and confinement times [needed for a plasma to generate fusion power] required significant improvements in forming and understanding plasmas confined by magnetic fields or by inertial techniques.[1]

Thus, research conducted on the prospects of fusion energy necessitated concurrent advances in the area of plasma physics, and, in fact:

> The international effort to achieve controlled thermonuclear fusion has been the primary stimulus to the development of laboratory plasma physics.[2]

The field of plasma physics has synthesized many areas of physics previously considered distinct disciplines: mechanics, electromagnetism, thermodynamics, kinetic theory, atomic physics, and fluid dynamics. Today, plasma physics goes beyond fusion research. Since most known matter in the universe is in the plasma state, plasma physics is central to our understanding of nature and to the fields of space science and astrophysics. Theories and techniques developed in plasma physics are providing fundamental new insights into classical physics and are opening up new areas of research.

The field of plasma physics has grown rapidly since the 1950s. When the American Physical Society formed the Division of Plasma Physics in 1958, for example, the division had less than 200 members. Today, the Division of Plasma Physics is one of the society's biggest groups, with almost 3,400 members. The careers of most of these members originated in magnetic fusion-related work. In addition, over 40 American universities now have major graduate programs in plasma physics and/or fusion technology. Graduate level plasma physics courses are also taught in applied mathematics and in electrical, nuclear, aeronautical, mechanical, and chemical engineering departments.

As shown in figure 6-1, the Department of Energy (DOE) has played a major role in plasma physics research, funding over three-quarters of federally sponsored plasma physics research in fiscal year (FY) 1984. Virtually all DOE support was directed at fusion applications; 72 percent of DOE's funding was dedicated to the magnetic fusion program, 26 percent funded the inertial confinement fusion program, and only 2 percent ($3 million, in 1984 dollars) was directed at general plasma physics. Outside of the fusion applications, Federal funding for plasma physics

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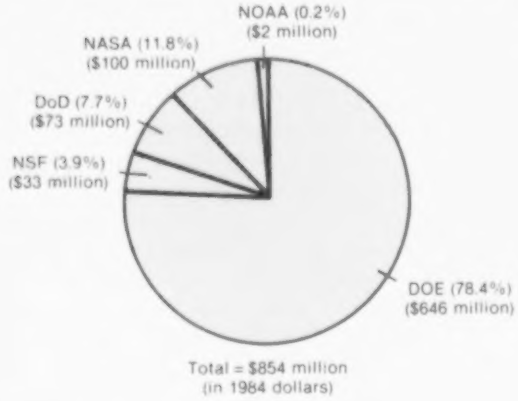
[1] National Research Council, *Physics Through the 1990s: Plasmas and Fluids* (Washington, DC: National Academy Press, 1986), p. 5.

[2] Ibid.

Figure 6-1.—Federal Funding of Plasma Physics in 1984



NOAA – National Oceanic and Atmospheric Administration
NASA – National Aeronautics and Space Administration
DoD – Department of Defense
NSF – National Science Foundation
DOE – Department of Energy

SOURCE: Adapted from the National Research Council, *Physics Through the 1990s: Plasmas and Fluids* (Washington, DC: National Academy Press, 1986).

research is very limited. A National Research Council report concluded that "support for basic plasma physics research has practically vanished in the United States," with only the National Science Foundation providing funds "clearly for this purpose."[3]

Educating Plasma Physicists

Educating plasma physicists, as well as other scientists and engineers, is one of the most widely acknowledged benefits of the fusion program. **Over the last decade, DOE's magnetic fusion program has supported the education of almost all of the plasma physicists trained in the United States.**[4] This achievement is due largely to DOE's commitment to maintaining university fusion programs during a period when budget reductions have forced other agencies to curtail their funding of plasma physics research. In addition, DOE provides 37 fusion fellowships annually to qualified doctoral students.

Although DOE supports the education of most of the Nation's plasma physics graduates, the department does not have the resources to employ many of these people. A large fraction of the Nation's plasma physicists are engaged in defense-related work;[5] plasma physicists also work in universities, private industry, and the National Aeronautics and Space Administration (NASA) space science program. Education in plasma physics and fusion research enables these scientists to "make major contributions to defense applications, space and astrophysical plasma physics, materials science, applied mathematics, computer science, and other fields."[6]

Advancing Science and Technology

Many high-technology R&D programs produce secondary benefits or "spin-offs." Spin-offs are not unique to particular fields of research, since extending the frontiers of practically any technology can lead to external applications. Although spin-offs may benefit society, they are unanticipated results of research and should not be viewed as a rationale for continuing or modifying high-technology research programs. Spin-offs may not be efficient mechanisms of developing new or useful technologies, compared to programs dedicated specifically to those purposes. Moreover, applications of new technologies are often drawn from several fields and may not be attributable to any particular one.

Over the years, fusion research has contributed to a variety of spin-offs in other fields. While the program cannot claim sole credit, each of the innovations listed below has at least one key element that came from the fusion program.[7]

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[3] Ibid., p. 97.

[4] John F. Clarke, Director, DOE Office of Fusion Energy, *Plasma Physics Within DOE and the Academy Report—Physics Through the 1990s*, Department of Energy, Office of Fusion Energy, July 1986, p. 5.

[5] Energy Research Advisory Board, *Review of the National Research Council Report: Physics Through the 1990s*, prepared by the Physics Review Board for the U.S. Department of Energy, February 1987, p. 44.

[6] Ronald C. Davidson, "Overview of Magnetic Fusion Advisory Committee Findings and Recommendations," presentation to Energy Research Advisory Board Fusion Panel, Washington, DC, June 25, 1986.

[7] This list is drawn from three reports: U.S. Department of Energy, Office of Energy Research, *Technology Spin-offs From the Magnetic Fusion Energy Program*, DOE/ER-0132, May 1982; U.S. Department of Energy, Office of Fusion Energy, *Technology Spinoffs From the Magnetic Fusion Energy Program*, DOE/ER-0132-1, February 1984; and U.S. Department of Energy, Office of Energy Research, *The Fusion Connection*, DOE/ER-0250, October 1985. For more information about the role of these technologies and others in magnetic fusion research, see ch. 4.

Contributions to Industry

Certain phenomena associated with fusion research have proven particularly applicable to the development of electronic systems and industrial manufacturing processes. *Plasma etching* is an important process in the semiconductor industry. Fusion research has provided information necessary to characterize and understand the process more completely and also has contributed plasma diagnostics that can be used to monitor the etching process.

Microwave electronics is another fusion contribution that has both civilian and military applications. Microwave tubes and plasmas share certain physical principles of operation, and advances in the understanding of basic plasma physics have contributed to improvements in microwave technology. The fusion program has also fostered development of the microwave industry through its requirements for high-frequency, high-power microwave sources, such as the gyrotron. Typical applications of microwave technology include high-power radar stations, television broadcasting, satellite communications, and microwave ovens.

Plasma physics phenomena studied in the fusion program also have significant applications in the plasma coating and surface modification of industrial materials. *Plasma coating* is important to the manufacturing industry because it may enable materials to better resist wear and corrosion. Finally, fusion experimental facilities use sophisticated power-handling technologies; electric utilities are interested in the near-term applications of these technologies.

Contributions to National Defense

Although magnetic fusion research has no direct application to military uses, the fusion program has contributed to the national defense. The most valuable contributions are in the background plasma physics research conducted by the fusion program and the education of scientists that later are hired by defense programs. In addition, many scientific ideas and technological developments being investigated under the Strategic Defense Initiative (SDI) grew out of research in the fusion program. For example, contributions made by the magnetic fusion program in the development of neutral beams and accelerators for free electron lasers have been instrumental to the development of directed-energy weapons necessary for SDI applications.

Contributions to Basic Science

Plasma physics is by now considered one of the core areas of physics research. Advances made in the fusion program in the understanding of plasma phenomena have been used by NASA, the Department of Defense (DoD), and others. Moreover, the fusion program has supported basic atomic physics research for more than two decades in order to develop detailed knowledge of fundamental atomic and molecular processes influencing plasma behavior.

Magnetic fusion research requires computational methods and facilities that are not available in other disciplines. Thus, the magnetic fusion program leads the way in the acquisition and use of state-of-the-art computers. The Magnetic Fusion Energy Computing Center's (MFECC) system of Cray computers and the satellite network system installed for these computers are important advances in computer technology. In addition, the fusion program has developed advanced computational methods in order to model and analyze plasma behavior.

Finally, fusion research has contributed to the development of plasma diagnostic technologies that have commercial, scientific, and defense applications. The demands of fusion research on diagnostic instrumentation are extremely exacting. Not only are plasmas very complex phenomena, but measurements of their characteristics must be made from the outside of the plasma so as not to affect it. Therefore, considerable development of sophisticated instrumentation has been required throughout the history of fusion research.

Stature

The stature of the United States abroad benefits from conducting high-technology research. The United States has been at the forefront of fusion R&D since the program was initiated in the

1950s. Maintaining a first-rate fusion program has placed the United States in a strong bargaining position when arranging international projects, has attracted top scientists from other fusion programs to the United States, and has enhanced the reputation of the United States in scientific and technical programs other than magnetic fusion.

NEAR-TERM COSTS

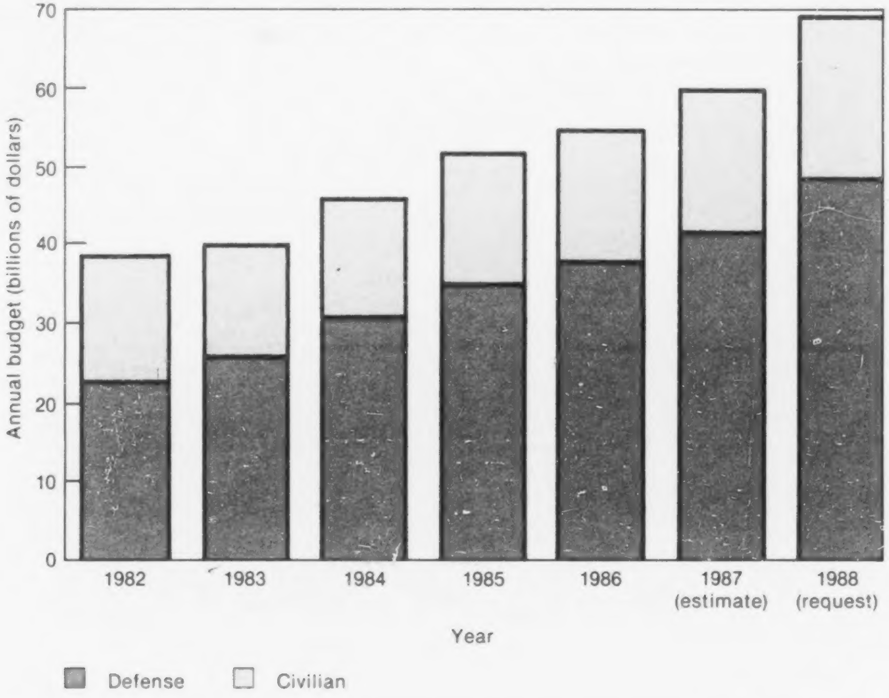
Magnetic Fusion Funding

The fusion program utilizes both financial and personnel resources. This section analyzes the monetary cost of fusion research by providing a sense of context for fusion expenditures. Fusion expenditures are compared to other government R&D programs and to energy R&D programs in particular.

Comparing Fusion to Other Government R&D

The Federal budget for R&D has grown steadily during the 1980s, in real terms. The bulk of this growth has been driven by increases in defense R&D spending, which almost doubled between 1982 and 1987. Non-defense R&D has also grown, though only 15 percent over the same period (see figure 6-2).

Figure 6-2.—Defense and Civilian Federal R&D Expenditures (in current dollars)

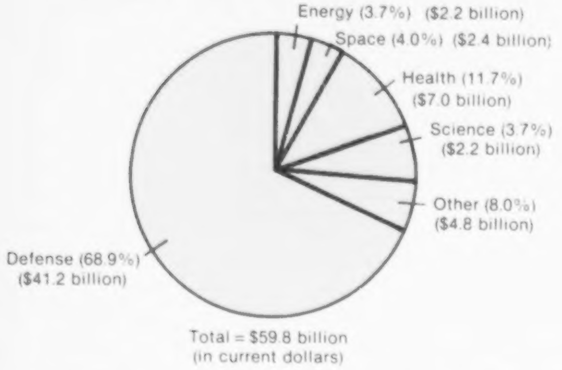


Defense: Department of Defense along with Department of Energy atomic energy defense activities.

Civilian: All other Federal R&D activities.

SOURCE: American Association for the Advancement of Science, *AAAS Report XII: Research and Development FY 1988* (Washington, DC: 1987).

Figure 6-3.—Major Components in Federally Funded R&D in Fiscal Year 1987



Defense:	Includes Department of Defense along with Department of Energy atomic energy defense activities.
Health:	Includes health research in the Department of Health and Human Services, Veterans Administration, Department of Education, and the Environmental Protection Agency
Space:	Includes the National Aeronautics and Space Administration, less space applications and aeronautical research (which are included in the "Other" category).
Energy:	Includes energy research in the Nuclear Regulatory Commission, Environmental Protection Agency, and Department of Energy, less general science and defense expenditures.
Science:	Includes National Science Foundation and Department of Energy general science (high energy physics and nuclear physics).

SOURCE: American Association for the Advancement of Science, *AAAS Report XII: Research and Development FY 1988* (Washington, DC: 1987)

Figure 6-3 shows the estimated fraction of the Federal research budget dedicated to various areas during FY 1987, and figure 6-4 depicts historical budget levels among these areas. It is estimated that the defense program will receive the largest portion, almost 70 percent, of Federal R&D funding in FY 1987. DoD will fund over 90 percent of this research, with the remainder funded by DOE. In FY 1987, defense-related activities will utilize one-half of DOE's R&D funding.

The next largest identifiable blocks of Federal R&D funding, each of approximately equal size, are space, health, energy, and general science research. Space activities are conducted by NASA. Most health-related research is conducted by the Department of Health and Human Services, through the National Institutes of Health (NIH). Most general science research is carried out by the National Science Foundation (NSF) and DOE's high energy physics and nuclear physics programs. DOE conducts most Federal energy R&D; the Nuclear Regulatory Commission and the Environmental Protection Agency also conduct limited energy research.

Those Federal R&D programs with budget authority estimated at over $200 million in FY 1987 are listed in table 6-1.[8] The intent of this table is to provide a context for the fusion program by depicting its relative funding commitment. The table is not intended to compare the magnetic fusion program to other programs, because the programs listed are not directly comparable. Some are near-term efforts; others—like fusion—are very long-term. Some, also like magnetic fusion, are focused on a single primary application; others, like the cancer research conducted by NIH, encompass a wide range of smaller subprograms. The balance between research and development varies considerably as well. DoD's large research, development, and testing programs include a small amount of research and a great deal of development and testing, whereas NSF's programs, for example, are almost entirely pure research.

As the table shows, the largest Federal R&D programs are defense-related. Magnetic fusion is DOE's fifth largest R&D program, following weapons R&D and testing, naval reactor development, high energy physics, and basic energy sciences.

Although table 6-1 provides a sense of scale between magnetic fusion research and other Federal R&D programs, it cannot be used to compare the programs themselves or the decisions by which these programs are funded. The criteria by which funding decisions are made in different agencies and departments are not consistent, and the degree of competition for funds between programs—either within a specific office or between offices, agencies, or departments—is difficult to measure. The budgets of different programs are prepared separately within the executive branch and considered separately in Congress.

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[8] A distinction is made between Budget Authority and Budget Outlay. Budget authority denotes how much a program could spend. In some cases, however, actual budget outlays (what the program did spend) will differ from the budget authority. A program may spend less than its budget authority, or more if it has accrued savings from previous years.

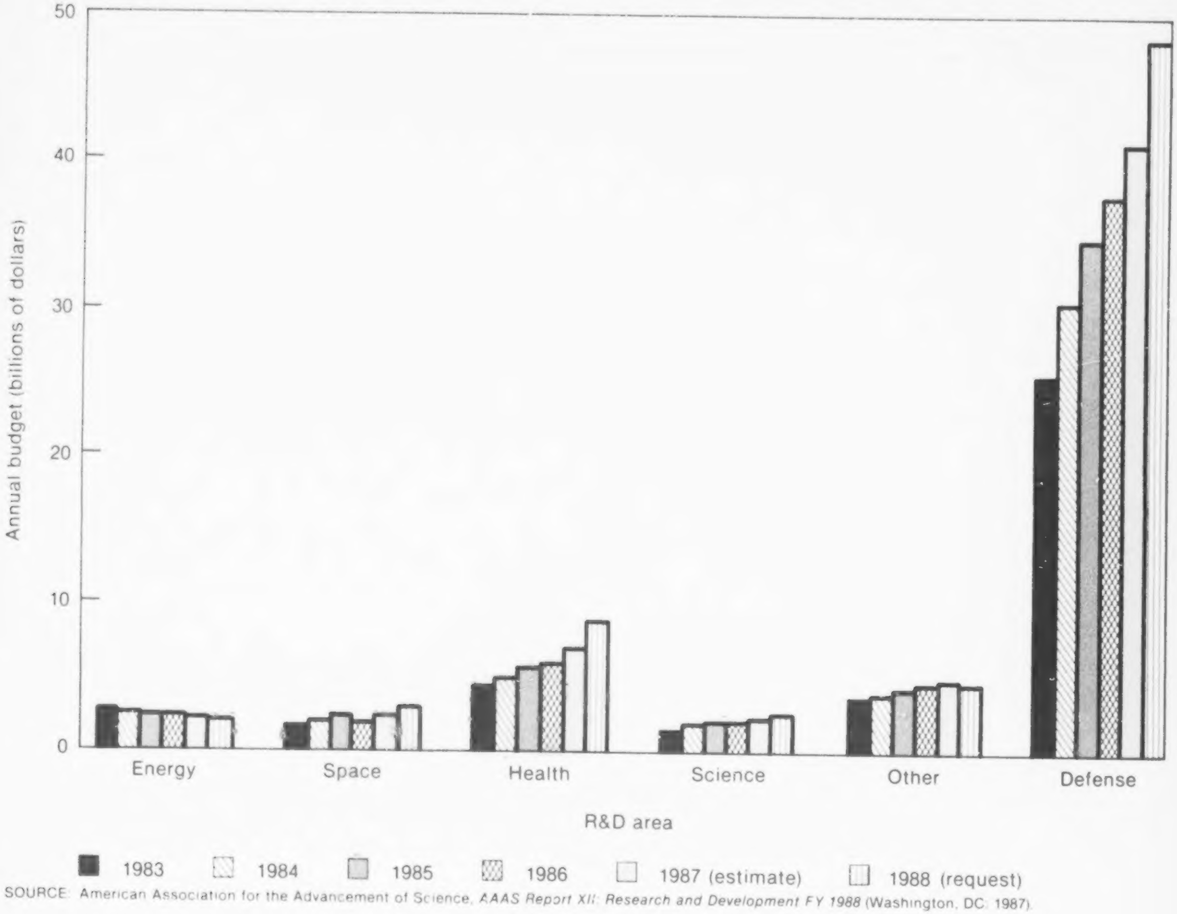

Figure 6-4.—Historical Component Funding Levels of Federal R&D Programs (in current dollars)

SOURCE: American Association for the Advancement of Science, *AAAS Report XII: Research and Development FY 1988* (Washington, DC: 1987).

Overall comparisons of one program to another are typically made only at the highest levels of aggregation, if at all.

In addition, this table does not represent a complete picture of all research undertaken by the U.S. economy. It only measures Federal investments, and in many programs there is substantial private sector involvement. Total private sector investment in R&D activities for 1987 is estimated at $60 billion, about the same as Federal R&D investment for that year.[9]

Comparing Fusion to Energy R&D

Since 1980, significant shifts in the emphasis of DOE appropriations have occurred. The department has focused more heavily than it did previously on atomic energy defense activities and less heavily on activities conducted by civilian programs, while overall DOE appropriations have decreased. Thus, civilian programs have competed for a smaller piece of a shrinking pie, resulting in serious financial pressure on civilian energy R&D. This shrinkage is in large part due to the Reagan Administration policy that development of near-term technology for civilian applications is better left to the private sector.

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[9] National Science Foundation, Division of Science Resources Studies, *Science and Technology Data Book 1987* (Washington, DC: National Science Foundation, 1986), NSF-86-311, figure 1, p. 3.

Table 6-1.—Federally Funded R&D Programs With Budget Authority Over $200 Million in Fiscal Year 1987

Research and development program name	Fiscal year 1987 budget estimate[a] (millions)
Department of Defense	$ 38,374.5
Army	($ 4,754.6)
Navy	($ 9,381.9)
Air Force	($ 15,416.8)
Defense agencies	($ 7,185.5)
Strategic Defense Initiative	[$ 3,743.4]
Defense Advanced Research Projects Agency	[$ 785.2]
Office, Secretary of Defense	[$ 569.1]
Defense Nuclear Agency	[$ 306.0]
National Aeronautic and Space Administration	$ 3,127.7
Space Station	($ 420.0)
Space Transportation Capability Development	($ 495.5)
Space Science and Applications	($ 1,552.6)
Physics and Astronomy	[$ 552.8]
Planetary Exploration	[$ 358.4]
Environmental Observations	[$ 320.9]
Aeronautics and Space Technology	($ 592.0)
Aeronautical research and technology	[$ 376.0]
Department of Energy	$ 5,561.1
Energy Supply R&D	($ 1,498.6)
Basic Energy Sciences	[$ 470.6]
Magnetic Fusion	**[$ 345.3]**
Nuclear Energy	[$ 325.9]
General Science and Research	($ 716.8)
High Energy Physics	[$ 499.7]
Nuclear Physics	[$ 217.1]
Atomic Energy Defense Activities	($ 2,785.7)
Weapons R&D and Testing	[$ 1,882.2]
Naval Reactors Development	[$ 563.8]
Department of Health and Human Services	$ 6,709.8
Alcohol, Drug Abuse and Mental Health Administration	($ 569.4)
General Mental Health	[$ 307.5]
National Institutes of Health	($ 5,853.2)[b]
Cancer	[$ 1,371.5]
Heart, Lung, and Blood	[$ 891.2]
Allergy and Infectious Diseases	[$ 535.6]
Diabetes, Digestive and Kidney Diseases	[$ 488.2]
Neurological and Communicative Diseases and Stroke	[$ 476.5]
Child Health and Human Development	[$ 352.5]
Eye	[$ 211.1]
Environmental Health Sciences	[$ 200.4]
National Science Foundation	$ 1,520.3
Mathematical and Physical Sciences	($ 463.4)
Biological, Behavioral, and Social Sciences	($ 257.7)
Geosciences	($ 284.6)
Department of Agriculture	$ 1,027.5
Agricultural Research Service	($ 523.3)
Cooperative State Research Service	($ 300.3)
Department of Interior	$ 362.2
Geological Survey	($ 208.6)
Department of Transportation	$ 285.2
Department of Commerce	$ 401.6
National Oceanic and Atmospheric Administration	($ 287.5)
Environmental Protection Agency	$ 343.4
Veterans Administration	$ 225.3
Agency for International Development	$ 224.2

[a] Values denoted with "( )" comprise programs included within the preceding department total, and values denoted with "[ ]" comprise subprograms included within the preceding program total. Only departments, programs, and subprograms with an annual budget over $200 million are listed; therefore, the listed program and subprogram budgets may not total the preceding departmental or program budget.

[b] Total program budget given for the National Institutes of Health includes an overall reduction of $67.1 million, which has not been allocated among individual Institute subprogram budgets in these figures.

SOURCE: American Association for the Advancement of Science, Intersociety Working Group, *AAAS Report XII: Research and Development FY 1988* (Washington, DC: American Association for the Advancement of Science, 1987).

Though magnetic fusion has fared better than many other energy programs, its budget has fallen significantly in recent years. From a peak of $659.7 million in FY 1977 (in 1986 dollars), funding for the fusion program has declined by over half, to a level of $319.1 million in FY 1987 (in 1986 dollars).[10] Figure 6-5 illustrates the recent budgets of DOE's larger energy R&D programs.

Unlike short-term energy development, the long-term, high-risk nature of the fusion energy program satisfies the criteria of the Reagan Administration's science and technology policy. Long-term, research-oriented programs like fusion have been able to maintain Federal budgetary support because, although there is a potentially high payoff, there is currently little incentive

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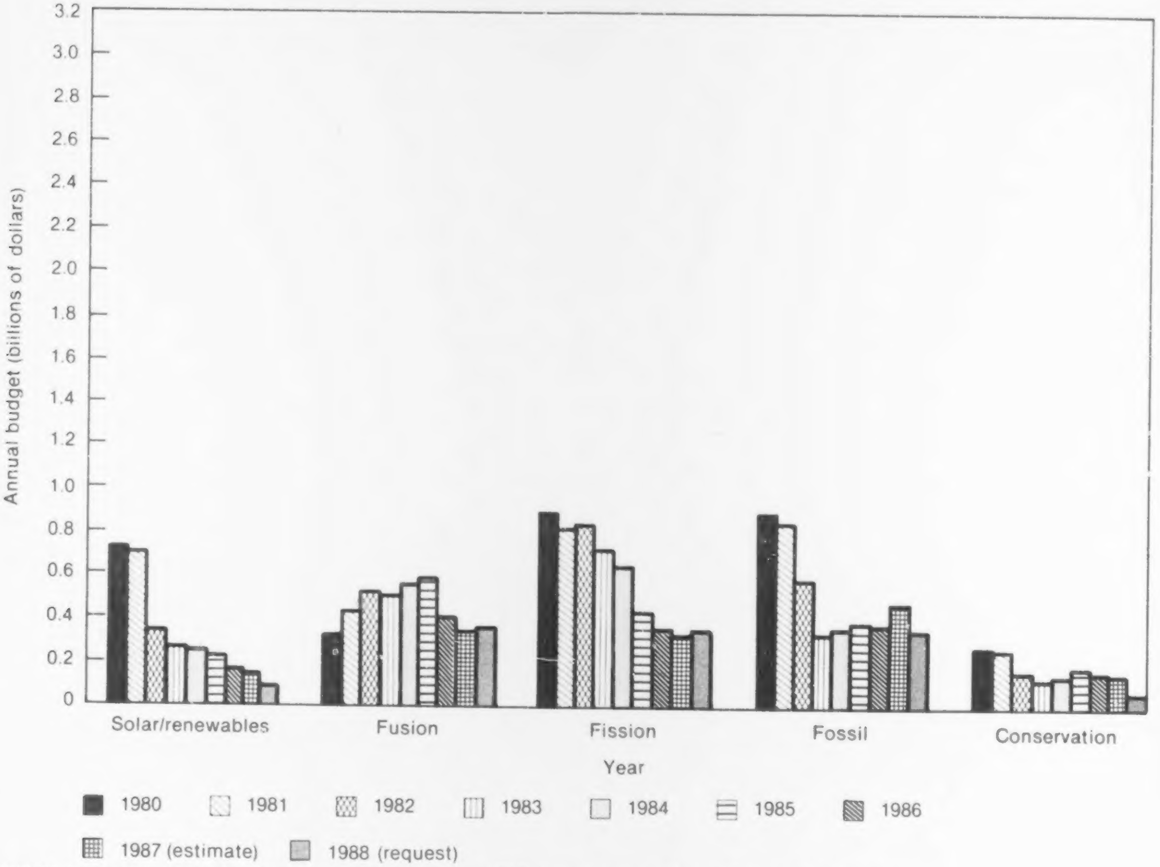
[10] Budget values and inflation indices were provided by J. Ronald Young, Director of the Office of Management, U.S. Department of Energy, Office of Energy Research, letter to the Office of Technology Assessment, Aug. 15, 1986.

Figure 6-5.—Annual Appropriations of DOE Civilian R&D Programs (in current dollars)



SOURCE: Argonne National Laboratory, *Analysis of Trends in Civilian R&D Appropriations for the U.S. Department of Energy*, 1986.

for industrial involvement. Even if the risks were not high, the benefits are so far off that their present value is not sufficient to interest private investors today. Virtually all fusion research is funded by the Federal Government. DOE's programs in nuclear energy, fossil fuels, conservation, and renewable energy, on the other hand, have lost much of their Federal support because it is believed that industry financing is appropriate in these cases.

Costs of Fusion Facilities

Table 6-2 lists the total construction costs of some representative fusion program experiments.[11]

The most expensive fusion projects to date are the Tokamak Fusion Test Reactor (TFTR) and the Mirror Fusion Test Facility (MFTF-B), which are an order of magnitude more expensive than other confinement experiments. In part, TFTR and MFTF-B were more expensive than other experiments because they required development of an extensive supporting infrastructure as well as construction of the actual device. In addition, these facilities are more advanced and much larger than the experiments constructed on alternative concepts.

The next facility the U.S. fusion program plans to construct, the Compact Ignition Tokamak (CIT), has an estimated cost of $360 million. It is proposed to be built at Princeton Plasma Physics

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[11] For information about the technical details of many of these projects, see ch. 4.

Table 6-2.—Cost of Representative Fusion Experiments

Experiment	Location	Type	Construction cost (millions of 1987 dollars)
Tokamak Facility Test Reactor	PPPL	Tokamak	$562
Mirror Fusion Test Facility-B	LLNL	Tandem Mirror	$330
Doublet III	GA	Tokamak	$ 56[a]
Doublet III-D (Upgrade)	GA	Tokamak	$ 36[a]
International Fusion Superconducting Magnet Test Facility	ORNL	Magnet Test[b]	$ 36[c]
Poloidal Divertor Experiment	PPPL	Tokamak	$ 54
Princeton Large Torus	PPPL	Tokamak	$ 43
Tritium Systems Test Assembly	LANL	Tritium Test[b]	$ 26
Tandem Mirror Experiment	LLNL	Tandem Mirror	$ 24
Tandem Mirror Experiment Upgrade	LLNL	Tandem Mirror	$ 23
Texas Experimental Tokamak	UT	Tokamak	$ 21
Advanced Toroidal Facility	ORNL	Stellarator	$ 21
TARA	MIT	Tandem Mirror	$ 19
ZT-40	LANL	Reversed-Field Pinch	$ 17
Alcator C	MIT	Tokamak	$ 15
Rotating Target Neutron Source	LLNL	Materials Test[b]	$ 11
Impurity Studies Experiment-B	ORNL	Tokamak	$ 5
Field Reversed Experiment-C	LANL	Field-Reversed Configuration	$ 3
Phaedrus	UW	Tandem Mirror	$ 1.8
Macrotor	UCLA	Tokamak	$ 1.5
IMS	UW	Stellarator	$ 1.4
Tokapole	UW	Tokamak	$ 0.6

KEY: PPPL—Princeton Plasma Physics Laboratory, Princeton, New Jersey
LLNL—Lawrence Livermore National Laboratory, Livermore, California
ORNL—Oak Ridge National Laboratory, Oak Ridge, Tennessee
GA—GA Technologies, Inc., San Diego, California
LANL—Los Alamos National Laboratory, Los Alamos, New Mexico
UT—University of Texas, Austin, Texas
MIT—Massachusetts Institute of Technology, Cambridge, Massachusetts
UW—University of Wisconsin, Madison, Wisconsin
UCLA—University of California, Los Angeles, California

[a] Values shown for the combined Doublet III facility and upgrade do not include an additional $54 million (in current dollars) of hardware provided by the government of Japan or $36 million (in 1987 dollars) for a neutral beam addition.

[b] These facilities are fusion technology facilities; all others on the table are confinement physics experiments.

[c] The cost of this facility does not include the cost of the six magnet coils that are being tested there. It is estimated that the magnet coils cost between $12 million and $15 million each (in current dollars).

SOURCE: U.S. Department of Energy, Office of Fusion Energy, 1987.

Laboratory, where it can take advantage of the lab's existing infrastructure. With initial construction funds requested in the FY 1988 DOE budget, CIT will be the largest fusion project undertaken in recent years.

Looking beyond CIT, the U.S. fusion program sees a next-generation engineering test reactor as necessary during the 1990s. Funding for this device, which is projected to cost well over a billion dollars, has not been requested by or appropriated to DOE. A recent DOE proposal to undertake international conceptual design and supporting R&D is currently being considered. If successful, international construction and operation of the device could follow the design phase of the project (see ch. 7).

Magnetic Fusion Personnel

The fusion program currently supports approximately 850 scientists (almost all Ph.D.s), 700 engineers, and 770 technicians.[12] These researchers work primarily at the national laboratories and in the university and college fusion programs. Because the size of the labor pool responds to shifts in the demand for labor, and because the long-term value of having a person work on one program as opposed to any other is difficult to measure, it is hard to quantify the implications of dedicating scientific and engineering manpower to the fusion program. The value of the fusion program for training plasma physicists, however, cannot be denied. **The fusion program trains far more people than it employs, and these people make valuable contributions in a variety of fields other than fusion.**

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[12] Thomas G. Finn, U.S. Department of Energy, Office of Fusion Energy, letter to the Office of Technology Assessment, Mar. 12, 1987. The number of technicians represents only full-time staff associated with experiments; shop people and administrative staff are not included. Figures for scientists and engineers include university professors and post-doctoral appointments; graduate student employees are not included.

According to DOE, since 1983 the number of Ph.D. staff positions at the major national fusion research centers has declined by almost 20 percent. Personnel levels among individuals without Ph.D.s, and the staffs of smaller fusion research centers, have also declined substantially. A recent study for the National Academy of Sciences predicts that if recent funding trends continue, the fusion program could lose 345 Ph.D.s between 1985 and 1991. Most fusion researchers who have left the fusion program have found work easily in other research programs within DOE and DoD. Many former fusion researchers are working on SDI. As the mobility of fusion researchers shows, these individuals have skills that are in demand in many areas.

PARTICIPATION IN MAGNETIC FUSION RESEARCH

DOE's Office of Fusion Energy (OFE) funds research conducted by three different groups: national laboratories, colleges and universities, and private industry. Each of these groups has different characteristics, and each plays a unique role in the fusion program.

Department of Energy National Laboratories

DOE's national laboratories play an important role both in the fusion program and in the department's general energy R&D. Figure 6-6 depicts DOE's distribution of laboratory funding among various subject areas. A list of DOE's major national laboratories, showing the extent of their fusion participation, is shown in table 6-3.

National laboratories are generally government-owned, contractor-operated facilities. Most of them were created during or shortly after World War II to conduct research in nuclear weapons and nuclear power development. Four DOE national laboratories have major research programs in magnetic fusion. It is estimated that these laboratories will conduct over 70 percent of the magnetic fusion R&D effort in FY 1987. According to DOE, the laboratories "are a unique tool that the United States has available to carry on the kind of large science that is required to address certain problems in fusion."[13] It is expected that the involvement of the national laboratories in the research program will remain important at least until the technology is transferred to the private sector for commercialization. The four major fusion laboratories are described below, in decreasing order of their share of the FY 1987 fusion budget.

Princeton Plasma Physics Laboratory

The Princeton Plasma Physics Laboratory (PPPL), located in Princeton, New Jersey, is one of the fusion program's oldest and most important facilities. It is located on Princeton University's James Forrestal Campus, and, in FY 1987, PPPL is estimated to receive the largest share of DOE's magnetic fusion budget of any single institution (27 percent).[14] PPPL is a program-dedicated laboratory, which means that virtually all of its research involves magnetic fusion. The bulk of PPPL's budget is used to operate TFTR, the largest U.S. tokamak experiment. TFTR is one of two operational experiments in the world designed to burn D-T fusion fuel, the other being the European Community's Joint European Torus.[15] In addition to TFTR, PPPL operates other smaller tokamak experiments.

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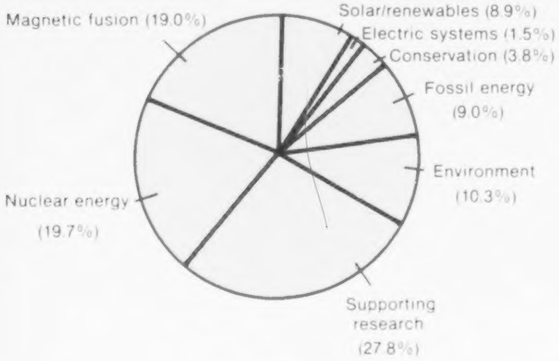
[13] John F. Clarke, Director, DOE Office of Fusion Energy, "Planning for the Future," *Journal of Fusion Energy*, vol. 4, nos. 2/3, June 1985, p. 202.

[14] Based on U.S. Department of Energy, FY 1988 Congression Budget Estimates for Lab/Plant, January 1987.

[15] Princeton Plasma Physics Laboratory, *An Overview: Princeton Plasma Physics Laboratory*, April 1985, p. 5. For more information on TFTR and other experiments, see ch. 4.

Figure 6-6.—Major DOE Civilian R&D Funding at National Laboratories in Fiscal Year 1987



Total = $1.3 billion
(in current dollars)

SOURCE: U.S. Department of Energy, Fiscal Year 1988 Congressional Budget Estimates for Lab/Plant, January 1987.

Lawrence Livermore National Laboratory

In FY 1987, it is estimated that Lawrence Livermore National Laboratory (LLNL), located in Livermore, California, will receive 15 percent of DOE's magnetic fusion energy budget.[16] LLNL has concentrated on tandem-mirror systems, and most of the experimental facilities at the laboratory have explored the capabilities of this confinement scheme.[17] The major magnetic fusion facility at LLNL is MFTF-B, a project that was mothballed in 1986, due to budget cuts, just weeks after construction was completed; MFTF-B has never operated. In addition to MFTF-B, there is another significant tandem-mirror facility at LLNL—the Tandem Mirror Experiment Upgrade (TMX-U), which has also been terminated. LLNL is now installing a small tokamak experiment and has been given responsibility for the design of the next-generation engineering test reactor. LLNL also operates the Magnetic Fusion Energy Computing Center for DOE. Moreover, LLNL conducts the largest component of the Nation's inertial confinement fusion research programs (see app. B).

Table 6-3.—DOE's Major National Laboratories

Laboratory	Location	Magnetic fusion research
Ames Laboratory	Ames, IA	None
Argonne National Laboratory	Argonne, IL	Minor
Bettis Atomic Power Laboratory	West Mifflin, PA	None
Brookhaven National Laboratory	Upton, NY	None
Fermi National Accelerator Laboratory	Batavia, IL	None
Hanford Engineering Development Laboratory	Richland, WA	Minor
Idaho National Engineering Laboratory	Idaho Falls, ID	Minor
Knolls Atomic Power Laboratory	Schenectady, NY	None
Lawrence Berkeley Laboratory	Berkeley, CA	Minor
Lawrence Livermore National Laboratory	Livermore, CA	Major
Los Alamos National Laboratory	Los Alamos, NM	Major
Mound Laboratory	Miamisburg, OH	None
Nevada Test Site	Mercury, NV	None
Oak Ridge National Laboratory	Oak Ridge, TN	Major
Pacific Northwest Laboratory	Richland, WA	Minor
Paducah Gaseous Diffusion Plant	Paducah, KY	None
Pinellas Plant	St. Petersburg,	None
Portsmouth Gaseous Diffusion Plant	Piketon, OH	None
Princeton Plasma Physics Laboratory	Princeton, NJ	Major
Rocky Flats Plant	Golden, CO	None
Sandia National Laboratory	Albuquerque, NM	Minor
Savannah River Plant	Aiken, SC	None
Stanford Linear Accelerator Laboratory	Stanford, CA	None

KEY: None - No magnetic fusion funding.
Minor - Fusion funding is less than $10 million in fiscal year 1987.
Major - Fusion funding is more than $10 million in fiscal year 1987.

SOURCE: Office of Technology Assessment, 1987.

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[16] Based on U.S. Department of Energy, FY 1988 Congressional Budget Estimates, op. cit.

[17] For technical information on the tandem mirror configuration, see ch. 4.

Photo credit: Princeton Plasma Physics Laboratory

Aerial view of the Princeton Plasma Physics Laboratory.

Oak Ridge National Laboratory

Oak Ridge National Laboratory (ORNL), located in Oak Ridge, Tennessee, conducts research across the full range of magnetic fusion program activities and is actively involved with national and international cooperation in virtually every area. The Advanced Toroidal Facility (ATF), when complete, will be ORNL's main experiment in toroidal confinement. It is anticipated that ATF, a stellarator, will make important contributions to the improvement of toroidal systems by increasing the understanding of fundamental confinement physics.[18] Contributing to this understanding are other ORNL programs in theory, diagnostics, and atomic physics. The ORNL technology program is fusion's largest, and it includes plasma heating and fueling, superconducting magnets, materials, and environmental assessment programs. In addition, ORNL is the host for the Fusion Engineering Design Center, which supports both reactor and next-generation device studies throughout the program. It is estimated that ORNL will receive about 15 percent of the magnetic fusion energy program's budget in FY 1987.[19]

Los Alamos National Laboratory

Los Alamos National Laboratory (LANL) is located in Los Alamos, New Mexico, and it contributes to DOE's fusion energy program in several ways. LANL has focused on alternative concepts. These concepts, not as far developed as the tokamak or mirror, are studied in several experiments at Los Alamos that are smaller and therefore less expensive than the large tokamak and mirror ma-

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[18] See ch. 4 for a technical description of the stellarator confinement concept.

[19] U.S. Department of Energy, FY 1988 Congressional Budget Estimates, op. cit.

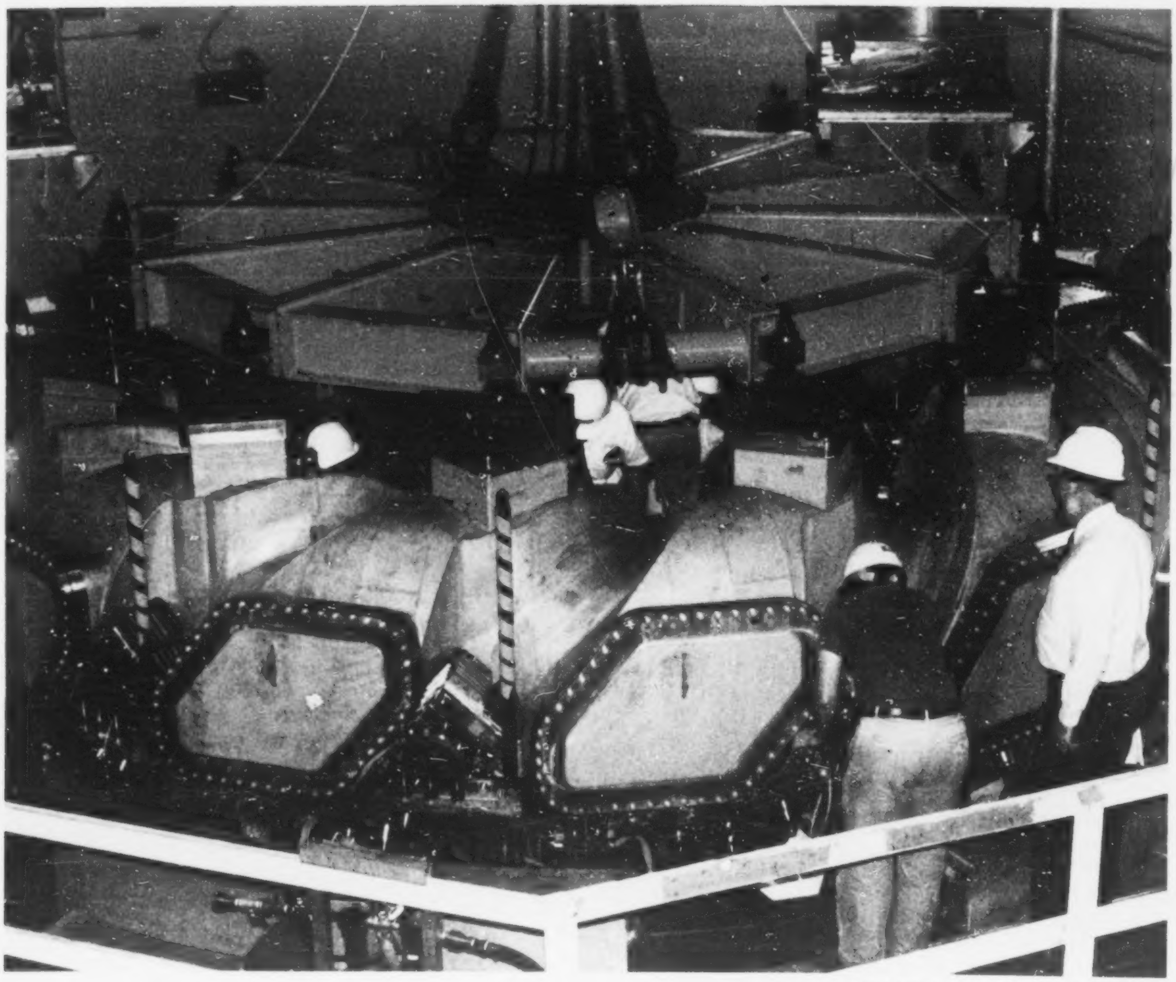

Photo credit: Oak Ridge National Laboratory

Assembly of The Advanced Toroidal Facility at Oak Ridge National Laboratory.

chines.[20] In addition, LANL conducts research in fusion technology and materials, studies reactor systems, and operates the Tritium Systems Test Assembly (TSTA)—a prototype of the tritium-handling apparatus necessary to fuel a D-T fusion reactor. In FY 1987, LANL will receive about 7 percent of the magnetic fusion energy program's budget.[21]

Universities and Colleges

Role in the Research Program

Universities and colleges contribute to many areas of energy research, including magnetic fusion. The role of these programs in fusion R&D activities differs significantly from the role of the national laboratories. Universities and colleges provide education and training and have been historically a major source of innovative ideas as well as scientific and technical advances. These programs could not replace the national labora-

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[20] Refer to ch. 4 for technical information on alternative confinement concepts.

[21] U.S. Department of Energy, FY 1988 Congressional Budget Estimates, op. cit.

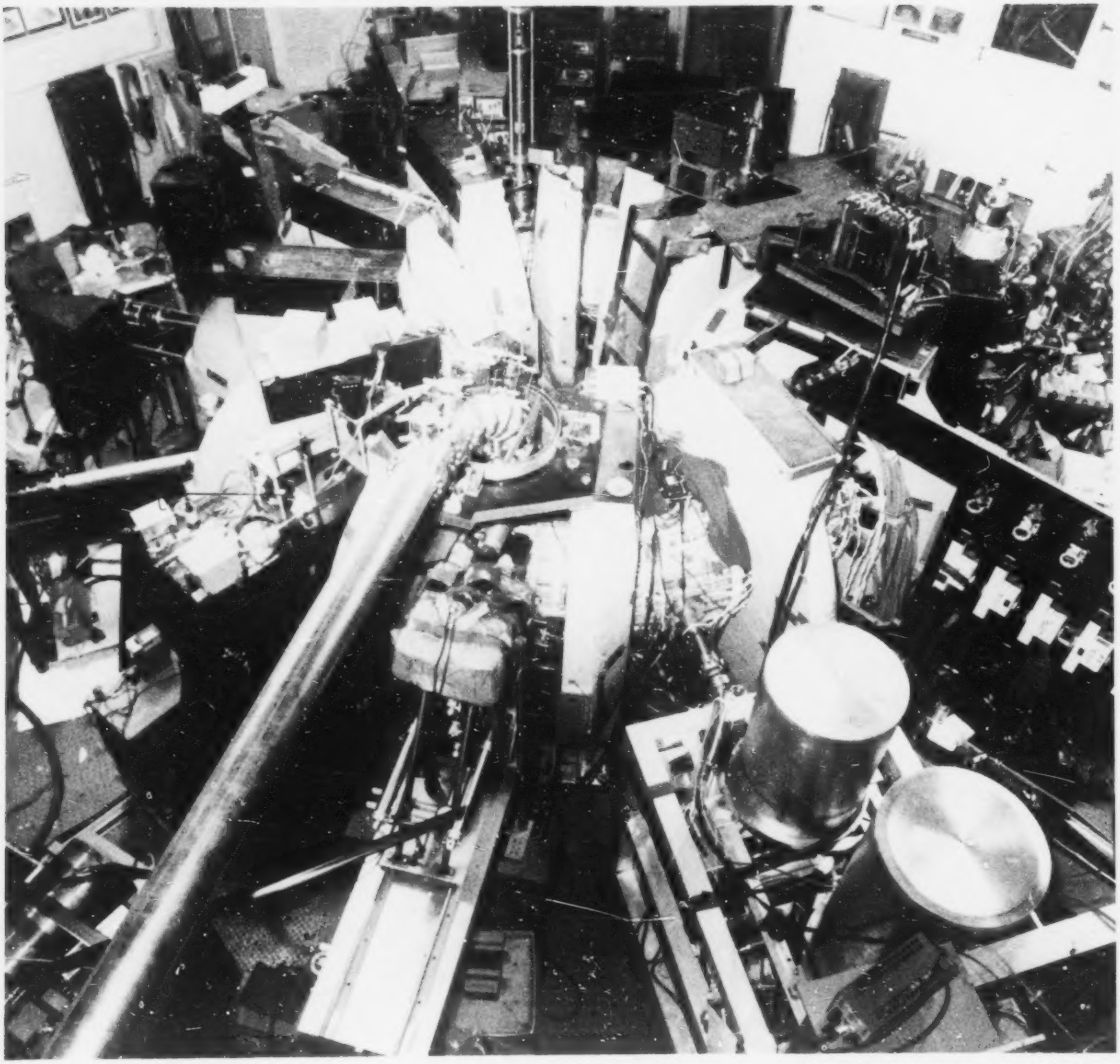

Photo credit: Los Alamos National Laboratory

ZT-40, a reversed-field pinch experiment located at Los Alamos National Laboratory.

tories, because it is difficult for a small university research program to construct and operate the large plasma devices that are needed to observe some of the important characteristics of plasma behavior. However, university and college fusion programs have made unique and important contributions to the research effort.

Among the university fusion contributions are the development of the high-field tokamak approach that will be utilized in CIT, the initial development of pellet fueling, and the development of various diagnostic technologies. In addition, university fusion programs have made important contributions on alternative confinement concepts. Overall, the Magnetic Fusion Advisory Committee (MFAC) Panel V found:

> The contributions from university-based experimental programs over the past decade have been significant, obviously cost-effective and have had a major impact on the development of fusion energy in general, and the large-scale or "mainline" experiments at the national laboratories in particular.[22]

University and college fusion programs also educate the young researchers in the field.

Table 6-4 lists the university and college fusion programs. It is estimated that these programs collectively will receive over 14 percent of the magnetic fusion budget in FY 1987 directly from DOE. In addition, university and college fusion programs could receive another 2 to 3 percent of

Table 6-4.—Universities and Colleges Conducting Fusion Research in Fiscal Years 1983 and 1986 (in 1986 dollars)

University or college	Fiscal year 1983 budget authority	Fiscal year 1986 budget authority
Massachusetts Institute of Technology	$26.6 million	$24.6 million
University of Texas	$ 6.9 million	$ 5.4 million
University of California—Los Angeles	$ 4.1 million	$ 6.2 million
University of Wisconsin	$ 4.1 million	$ 4.8 million
University of Maryland	$ 1.9 million	$ 983,000
New York University	$ 1.3 million	$ 1.1 million
Columbia University	$ 1.1 million	$ 1.2 million
University of Washington	$ 776,000	$ 708,000
Cornell University	$ 760,000	$ 535,000
University of California—Berkeley	$ 618,000	$ 438,000
Johns Hopkins University	$ 483,000	$ 340,000
University of California—Irvine	$ 481,000	$ 147,000
Rensselaer Polytechnic Institute	$ 353,000	$ 392,000
California Institute of Technology	$ 351,000	$ 503,000
Georgia Institute of Technology	$ 271,000	$ 115,000
Pennsylvania State University	$ 263,000	$ 97,000
University of California—Santa Barbara	$ 241,000	—
University of Illinois	$ 226,000	$ 335,000
Auburn University	$ 212,000	$ 372,000
University of Missouri	$ 201,000	$ 239,000
University of California—San Diego	$ 175,000	$ 240,000
Yale University	$ 123,000	$ 50,000
University of Arizona	$ 115,000	$ 13,000
College of William and Mary	$ 95,000	$ 18,000
University of Connecticut	$ 90,000	$ 80,000
Western Ontario University	$ 78,000	—
University of Michigan	$ 66,000	—
Wesleyan University	$ 63,000	$ 50,000
Stanford University	$ 60,000	$ 13,000
University of Iowa	$ 30,000	—
University of Virginia	$ 30,000	—
State University of New York—Buffalo	$ 24,000	—
Dartmouth College	$ 14,000	$ 60,000
University of Colorado	—	$ 60,000
North Carolina State University	—	—
Stevens Institute of Technology	—	$ 15,000
Syracuse University	—	$ 101,000
University of New York City	—	$ 25,000
Total university and college budget	$52,322,000 (33 programs)	$49,301,000 (30 programs)

SOURCE: Fiscal year 1983 budgets from Magnetic Fusion Advisory Committee Panel V, Principal Findings and Recommendations of the MFAC Subpanel Evaluating the Long-Term Role of Universities in the Fusion Program, July 1983, p. 9. Fiscal year 1986 budgets provided by DOE's Office of Fusion Energy, FY 1988 Congressional Budget Contractor Summary, Jan. 16, 1967.

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[22] Magnetic Fusion Advisory Committee Panel V, *Principal Findings and Recommendations of the Magnetic Fusion Advisory Committee Subpanel Evaluating the Long-Term Role of Universities in the Fusion Program*, July 1983, p. 18. The Magnetic Fusion Advisory Committee is a committee of fusion scientists and engineers that provide technical advice to DOE's Office of Fusion Energy.

the fusion budget indirectly through subcontracts from the national laboratories. The programs conducted by the universities in fusion are diverse, varying in funding level and research area. Over 80 percent of the university programs received less than $1 million each from DOE in FY 1986.

Recent budget cuts have seriously affected university and college fusion programs, which have suffered larger percentage budget reductions than the fusion program as a whole. University funding was $49.3 million in FY 1986, is estimated at $44.7 million in FY 1987, and is requested to be $41.7 million in FY 1988, in current dollars. The last two figures represent percentage decreases of 9 and 7 percent, respectively.[23] The corresponding decreases for the overall fusion budget ($361.5 million in FY 1986, an estimated $341.4 million in FY 1987, and a requested $345.6 million in FY 1988, in current dollars) are 6 percent and −1 percent.

For university and college fusion programs, DOE is the only source of financial support. NSF, the other likely Federal support agency, does not fund fusion research because it is considered applied, as opposed to basic, research and because it is believed to be DOE's area. Thus, given recent budget cuts, two-thirds of the university and college programs have either reduced or eliminated their programs since 1983. Seven colleges have eliminated their fusion programs, while five new programs have been added. It is anticipated by University Fusion Associates (UFA), an informal grouping of individual fusion researchers from universities and colleges, that if current funding trends continue, as many as half of the colleges and universities will eliminate their fusion research programs between 1986 and 1989.[24] DOE has stated that it intends to maintain the university fusion budget at a constant level (corrected for inflation) and does not foresee any need for additional programs to drop out. In any case, continued tight budgets and the loss of university programs reduces the ability of the fusion program to attract and educate new researchers.

In response to the funding cuts and the narrowing of the fusion program's scope, UFA has recommended that "approximately 3 to 5 percent additional funding should be added back into the fusion budget to support innovative and new ideas."[25] According to UFA, one of the most urgent uses of this money would be to provide seed money to innovative research proposed by universities, national laboratories, and private industry. UFA contends that this funding would help preserve some of the small university programs endangered by budget cuts, as well as create the atmosphere of excitement necessary to attract top students to the field. This idea has been endorsed by other members of the fusion community.

Given recent budgets, university and college fusion programs are concerned about the future direction of DOE's fusion program. In particular, representatives of UFA worry that the role of university fusion programs may be difficult to preserve if the Federal fusion program becomes more dependent on international cooperative projects. The international activities of college and university fusion programs are generally small-scale, and it is not clear how these activities could fit in a collaborative engineering test reactor effort.

University and College Activities

Universities and colleges have made contributions to fusion research in a variety of areas. In tokamak development, university fusion programs have worked on radiofrequency heating and current drive, boundary physics, high beta stability, and transport of heat and particles in fusion plasmas.[26] The largest university tokamak experiments are MIT's Alcator project, the Texas Experimental Tokamak (TEXT) experiment at the University of Texas, and Macrotor at the University of California at Los Angeles (UCLA).

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[23] If the Massachusetts Institute of Technology (MIT), the largest university fusion program, is not included, the university fusion budget decreases in FY 1987 and FY 1988 are 7 and 2 percent, respectively.

[24] George H. Miley, testimony on *Fiscal Year 1987 Department of Energy Authorization (Magnetic Fusion Energy)*, Hearings before the Subcommittee on Energy Research and Production, House Science and Technology Committee, 99th Cong., 2d sess., vol. 5, Feb. 26, 1986, p. 103.

[25] Ibid., p. 100.

[26] For more information on the technical aspects of these contributions, see ch. 4.

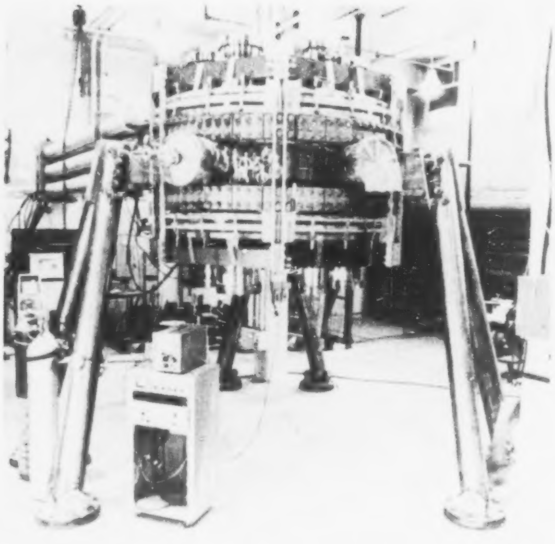

Photo credit: Plasma Fusion Center, MIT

The Alcator C tokamak at the Massachusetts Insititute of Technology.

In addition to tokamak research, a small group of universities is exploring the mirror confinement concept. The TARA facility at MIT and Phaedrus at the University of Wisconsin are the major university mirror experiments and, since the mothballing of the mirror machines at LLNL, have become the only U.S. mirror experiments. Support for university mirror programs has decreased, however. In fact, in the budget for FY 1987, DOE proposed elimination of funding for these university-based mirror projects. Congress has made additional funds available to keep both operational throughout FY 1987, and it appears that Phaedrus will remain operational throughout FY 1988 as well.

Several universities also study other confinement concepts for fusion reactors, including the stellarator, compact toroid, and reversed-field pinch. Work in these concepts is conducted at the University of California at Irvine, UCLA, Cornell University, University of Maryland, Pennsylvania State University, University of Illinois, University of Washington, and University of Wisconsin.

Finally, several university programs are exploring technology development and atomic physics. Programs at the University of Arizona, Auburn University, University of California at Santa Barbara, UCLA, Georgia Institute of Technology, University of Illinois, MIT, University of Michigan, Rensselaer Polytechnic Institute, University of Washington, and University of Wisconsin focus on reactor systems, materials, surface effects, and superconducting magnets.

Private Industry

Role in the Research Program

Private industry can take a variety of different roles in fusion research, depending on its level of interest and the stage of development. The most useful roles fall into three main categories.[27] These categories, along with the principal functions performed in each category, are listed in table 6-5.

Industry as Advisor.—The advisory role of private industry is filled frequently by corporate executives who are asked to help assess various stages of program development. The principal benefit of the advisory role is the development of appropriate program goals. As a support services contractor, industry assigns individuals or small groups to work in direct support of a manager at DOE or at a national laboratory. Private industry also provides members of its technical staffs to serve on technical committees, such as

Table 6-5.—Industrial Roles and Functions

Roles	Functions
Advisor	Support services contractor Advisory committee
Direct participant	Materials supplier Component supplier and manufacturer Subsystems contractor Prime contractor, project manager Facilities operator Customer
Sponsor	Research and development

SOURCE: Argonne National Laboratory, Fusion Power Program, *Technical Planning Activity: Final Report*, commissioned by the U.S. Department of Energy, Office of Fusion Energy, ANL/FPP-87-1, 1987, table 7-4, p. 340.

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[27] Argonne National Laboratory, Fusion Power Program, *Technical Planning Activity: Final Report*, commissioned by the U.S. Department of Energy, Office of Fusion Energy, ANL/FPP-87-1, 1987, pp. 340-343.

the Magnetic Fusion Advisory Committee (MFAC) or the Energy Research Advisory Board (ERAB). Through advisory arrangements, DOE gains industry's expertise and skills, and industry gains knowledge, contacts, and income. However, there is no commitment in this type of advisory relationship that the advice will be used by DOE or the national laboratories.

Industry as Direct Participant.—To become major participants in the fusion program, industry executives must understand near-term program objectives and be willing and able to contribute to the achievement of these objectives. Industry's direct participation will be particularly important during the engineering phase of the research program, when information and expertise must be transferred to industry from the national laboratories and universities.

As a direct participant, industry can serve a variety of functions. It can supply off-the-shelf components, as well as design and manufacture components made to customer-supplied specifications. One form of direct participation, which industry sees as most valuable, allows the customer (e.g., DOE, a national laboratory, or eventually an electric utility) to define a project and to assign responsibility for the task to a company. Industry can also act as a prime contractor or project manager; in this case, industry is directly responsible to a customer for defined aspects of management, engineering, fabrication, and installation of a product, such as a fusion device or power reactor.

Industry as Sponsor.—The most extensive level of industrial involvement will be the sponsorship of private R&D activities. Sponsorship includes the contribution of direct funds, labor, or both. As a sponsor, industry finances its own research program independently, whereas as a direct participant industry's activities are largely financed by the Federal Government. Sponsoring privately funded R&D requires confidence in the eventual profitability of the technology.

Current Industrial Activities

To date, industrial involvement in fusion research primarily has been advisory, with limited cases of direct participation. Industry representatives serve on the Energy Research Advisory Board and the Magnetic Fusion Advisory Committee, both of which advise DOE on the fusion program. Other industrial participation is facilitated through sub-contracts from national laboratories.

Only one private company, GA Technologies of San Diego, California, participates significantly in fusion research. GA Technologies is a private firm that conducts fusion research under Federal contract. In this sense, GA has been compared to a national laboratory in the field of fusion research. The company became involved in fusion research during the 1950s, when the energy applications of fusion were thought to be closer. Because GA Technologies (then called General Atomic Corp.) was able to assemble a high-quality team of fusion scientists and engineers, the Federal Government has funded the bulk of its fusion research since 1967, when GA lost its primary source of private fusion support. In FY 1987, GA Technologies received 10 percent of DOE's fusion budget.

The fusion program at GA Technologies consists primarily of tokamak confinement research; GA operates the Doublet III-D (D III-D) tokamak, which is the second largest tokamak in the United States.[28] D III-D is also the largest U.S. international project. Japan and the United States, through GA Technologies, have jointly financed and operated the D III-D facility since 1979.[29]

In addition, GA Technologies and Phillips Petroleum Co. invested over $30 million in inventing, fabricating, developing, and operating the Ohmically Heated Toroidal Experiment (OHTE) at GA. OHTE is the only major fusion experiment constructed and operated largely with private funds. OHTE was completed in 1982 and operated until 1985. In 1985, GA and Phillips requested financial support from DOE for further development of the concept. However, DOE would not fund this additional work, initiating a comparable program at LANL instead. Without

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[28] The Tokamak Fusion Test Reactor (TFTR) at Princeton Plasma Physics Laboratory is about twice as large as D III-D.

[29] For more information on the international cooperation aspects of GA's D III-D experiment, see ch. 7, pp. 162-163.

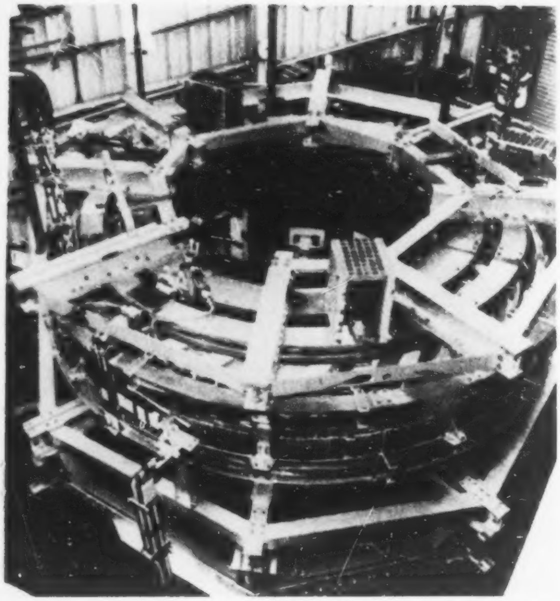

Photo credit: GA Technologies

OHTE fusion device at GA Technologies, San Diego, California.

Federal financial support, OHTE was discontinued. In mid-1986, DOE agreed to provide GA with a grant to operate OHTE, and the experiment was restarted. Recently, DOE decided not to renew GA's operating grant for OHTE after FY 1987; it is anticipated that the experiment will be permanently mothballed.

At this stage in the research program, other private companies have found no compelling reason to sponsor fusion research. Even GA Technologies' involvement would be severely limited were it not for extensive Federal funding. Neither are electric utilities currently conducting fusion research. By 1986, the Electric Power Research Institute (EPRI), a utility-funded research organization, had phased out what had been a $4 million per year program. According to the former EPRI fusion manager, EPRI is unwilling to spend money on fusion because the energy applications are so long-range.[30] Individual utilities are not conducting fusion research either, because of the large investment required and the difficulty of convincing regulatory agencies to allow research costs to be transferred to ratepayers.

An MFAC panel on industrial participation in fusion noted that:

> . . . fusion commercialization is sufficiently far in the future and fusion technology sufficiently specialized so that significant cost sharing [between the Federal Government and the private sector] should not be expected. The government and its national laboratories are the immediate customers and should pay the full cost of received products and services.[31]

The position of industry, at least until commercialization is closer, appears to be a subordinate role supporting the national laboratories and universities.

The role of industry in the U.S. fusion program is completely different from its role in the Japanese program, where mechanisms for technology transfer from government to industry have been institutionalized. In Japan, the Japan Atomic Energy Research Institute (JAERI) and various national laboratories and universities conducting fusion research contract with industry to do all the design, research, and development that is necessary. As in the United States, the financial contribution of Japanese industry to fusion research is small. However, its role is critical; according to one JAERI official, the Japanese Government's role is limited to "resolving what type of machine is needed and designing it," and even this task is "shared" with industry.[32] Thus, Toshiba, Hitachi, and Mitsubishi are intimately involved in fusion research.

In the United States, in contrast, fusion is primarily a government research program. The national laboratories maintain large engineering staffs and have strong manufacturing capabilities.

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[30] F. Robert Scott, "Industry and Utility Perspectives on Future Directions in Fusion Energy Development," *Journal of Fusion Energy*, vol. 5, No. 2, June 1986, p. 138.

[31] Magnetic Fusion Advisory Committee Panel VII, *Report on Industrial Participation in Fusion Energy Development*, May 1984, pp. 5-2 to 5-3.

[32] Unnamed Japanese official, quoted in Fiona H. Jarrett's *International Collaboration in Magnetic Fusion Energy: The Industrial Role. A Strategy for Industry Participation in an International Engineering Test Reactor Project*, prepared for the U.S. Department of Energy, Office of Fusion Energy, August 1986, p. 15.

DOE has only a limited role at present for involving industry in fusion research; industrial participation is typically ad hoc. Due to the budget cuts in recent years, the role of industry has been additionally limited, both because of the few major new projects undertaken and because constricted budgets have made the national laboratories reluctant to subcontract to industry. The role of industry in the U.S. fusion program is not institutionalized.

Establishing an Industrial Base for Fusion

Under current administration policy, the private sector will be responsible for the demonstration and commercialization of fusion technology. As discussed in chapter 5, it is important to establish an industrial capacity on which the private sector can base its development efforts. An MFAC panel on industrial participation in fusion research concluded that:

> . . . if a utility is to invest capital to build a fusion prototype or power plant, it must have confidence in its suppliers. This confidence can be established only if the suppliers have been qualified through active participation in the fusion program and have a record of furnishing quality goods and services.[33]

Currently, there is controversy over how to prepare the industrial base. In particular, **there is extensive disagreement over the timing of industrial participation in the research program prior to the demonstration and commercialization stages.**

For the research phase of fusion development, many fusion scientists contend that industry should be an advisor or low-level direct participant supporting national laboratories and universities. Given the current budget situation and the nature of the research to be completed before demonstration and commercialization, these individuals believe that there are not enough opportunities appropriate for industry to develop and maintain a standing capability in fusion. Moreover, since the private sector is reluctant to invest its own funds, proponents of this position maintain that it is too early in the program to encourage substantial industrial participation. They predict that as demonstration and commercialization approach, industry will naturally become more interested in the applications of fusion technology, hopefully to the point where they are willing to invest money to explore the technology's potential. These individuals believe that limiting industry's participation in the near-term will not preclude its eventual role in demonstration or commercialization; they believe premature industrial involvement could be detrimental.

Others argue that it is essential to involve industry in the research effort before the demonstration stage. The proponents of early industrial involvement stress that technology transfer should occur from the national laboratories and universities to private industry at all stages of the research program, and that such transfer cannot be effective without active industrial participation. The willingness of industry to invest in the technology should not be used as a criteria for determining the appropriate degree of involvement, these people argue, because industry needs information and expertise to accurately assess the value of the technology.

According to these individuals, early involvement of industry and utilities ensures that the technology developed will be marketable by vendors and attractive to its eventual users. Technology transfer will take time; if this transfer is not started until after completion of the research program, fusion's overall development could be delayed. In addition, proponents of this position-cite a variety of near-term benefits of industrial participation, including increasing support for the fusion program, facilitating spin-offs from fusion to other technologies, and transferring skills acquired by industries involved in fusion to other areas of high-technology such as aerospace and defense.

The impact of various levels of industrial participation in the research program on the successful commercialization of fusion technology cannot be determined now. Since the mechanisms for transferring responsibility for fusion's development from the Federal Government to the private sector are not yet known, the impact of early industrial participation on the pace and effectiveness of this transfer is unclear. However, even without linking near-term industrial participation in research to the success of future development, a well-established industrial base must be in place before the private sector can demonstrate and commercialize fusion technology. If the industrial base is insufficient, it will not only be difficult for industry to construct and operate a demonstration reactor, but the customers (probably electric utilities) will be reluctant to purchase fusion reactors.

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[33] Magnetic Fusion Advisory Committee Panel VII, op. cit., pp. 2-4.

SUMMARY AND CONCLUSIONS

Fusion research has provided a number of near-term benefits such as development of plasma physics, education of trained researchers, contribution to "spin-off" technologies, and support of the scientific stature of the United States. However, fusion's contributions to these areas does not imply that devoting the same resources to other fields of study would not produce equivalent benefits. Therefore, while near-term benefits do provide additional justification for conducting research, it is hard to use them to justify one field of study over another.

Virtually all of the money spent on fusion research in the United States comes from the Federal Government. The fusion program is DOE's fifth largest research program, and in recent years the program has been relatively well-funded compared to DOE's other energy R&D programs. Nevertheless, the budget for magnetic fusion R&D has fallen by about a factor of 2 since 1977 (in constant dollars). These budget decreases have severely constrained program activities.

Funding limitations have affected the activities of all three major groups that conduct fusion research: national laboratories, universities and colleges, and private industry. Few new construction projects have been initiated in recent years, and research in some areas (particularly mirror fusion) has been curtailed or eliminated. Moreover, many researchers have left fusion. Budget cuts have also interfered with the attainment of the program's near-term goals. In particular, the ability of the fusion program to attract new researchers to its university programs and to train them has suffered. Constrained budgets also limit the participation of industry in fusion research. In addition, the United States is no longer the undisputed leader in fusion research; the Japanese and European fusion programs have caught up with—and may have even surpassed—the U.S. effort.

OTA has not evaluated whether Federal fusion research funds are being spent in the most effective and efficient manner. Neither has it evaluated the appropriate priority to be given to fusion research as compared to other research programs. Comparisons among R&D programs are difficult to make and are typically not made explicitly during the budgetary process. Therefore, comparative funding levels do not necessarily provide an indication of relative priority. The appropriate funding level given to fusion research depends on the motivations and goals of the program. It also depends on where the money will come from—whether from cutting other programs or from additional sources of revenue—and the impacts of these funding choices reach far beyond the program itself.

Chapter 7

Fusion as an International Program

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Chapter 7

Fusion as an International Program

INTRODUCTION

Many nations of the world have cooperated on magnetic fusion research for almost 30 years. Since U.S. magnetic fusion research was declassified in 1958, the major international programs have engaged in regular information and personnel exchanges, meetings, joint planning efforts, and jointly conducted experiments.[1]

The leaders of the U.S. fusion community continue to support international cooperation, as does the U.S. Department of Energy (DOE). In the past, the United States cooperated internationally on a variety of exchanges that have produced useful information without seriously jeopardizing the autonomy of the domestic fusion program. In recent years, in response to budgetary constraints and the technical and scientific benefits of cooperation, DOE has begun cooperating more intensively in fusion, and the major fusion programs have become more interdependent. **For the future, DOE proposes undertaking cooperative projects that will require the participating fusion programs to become significantly interdependent; indeed, DOE now sees more intensive international collaboration as a financial necessity.**

Why Cooperation Is Attractive

Without exception, all of the major fusion programs participate in international activities and look favorably on more intensive future activities. There are several reasons for this widespread interest.[2]

Fusion Research Is Expensive

The high cost of fusion research is a practical incentive for nations to cooperate. The next-generation engineering test reactor, for example, is expected to cost well over $1 billion and possibly several times that much, requiring a substantial increase in U.S. annual fusion budgets if it were to be built domestically. It is not clear whether or not the governments of any of the major fusion powers would be willing to construct such an expensive experiment alone. Given the expense and considering the similarity in next-step program goals, the major fusion programs have agreed in principle that the world does not need four engineering test reactors of the same kind. Limited funding can be allocated more efficiently if nations are willing to collaborate on one major experimental facility.

Fusion Programs Are at Comparable Levels

The comparable levels of progress among the major fusion programs make higher levels of cooperation attractive, particularly over the next decade. While there are differences in emphasis and achievement, the programs have comparable scientific and technical capabilities and recognize the need for similar next-generation experiments. Cooperative projects are easier to implement in complementary programs because the benefits can be distributed equitably and because all participants stand to gain from their partners' expertise.

Fusion Can Advance More Effectively

International collaboration in fusion research is attractive because it provides a forum for scientists and engineers to interact. If the major programs can coordinate their activities, the intellectual resources available to address pressing issues in fusion research and development (R&D) can increase dramatically.

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[1] Major fusion programs are currently active in the United States, Japan, the European Community (EC), and the Soviet Union. Primary contributors to the European Community's fusion program are the Federal Republic of Germany, France, Italy, and the United Kingdom, although other member nations are also involved.

[2] The reasons that follow were based in part on a discussion of incentives to collaborate found in: Energy Research Advisory Board, *International Collaboration in the U.S. DOE's Research and Development Programs*, report to the U.S. Department of Energy, prepared by the ERAB International Research and Development Panel, DOE/S-0047, December 1985, p. 11.

Forms of Cooperation

International cooperative efforts range from simply exchanging information in international meetings through the joint construction and operation of experimental devices to complete integration of research efforts.[3] Various types of cooperation entail different levels of program integration, information transfer, and trust. The potential risks and benefits of the programs vary correspondingly.

It is necessary to make a distinction between the terms "cooperation" and "collaboration." This report will adopt the usage of a recent National Research Council report on cooperation in fusion research.[4] Throughout this OTA assessment, "cooperation" will refer to all activities involving nations, or individuals from different nations, working together. "Collaboration," a more intensive type of cooperation, will describe activities involving a substantial degree of program integration, funding commitment, and joint management.

Types of Cooperation and Collaboration

- **Information Exchange.** Information exchange is the most common form of international cooperation. Information on achievements and advances, as well as technical approaches and experimental data, is exchanged through several channels, including meetings, conferences, symposia, workshops, and publication in technical journals.
- **Personnel Exchange.** Personnel exchanges—visits and assignments—also are widely used. During a typical visit, research scientists tour one or more of the host program's facilities for 1 or 2 weeks. Assignments are extended stays in which the guest participant actually works on an experiment and contributes to the host program's research effort. For the duration of the assignment, the guest participant is a full-fledged member of the experimental or theoretical team. Assignments are one of the most effective ways to transfer expertise.
- **Joint Planning.** Joint planning includes activities to identify areas for future cooperative research, to provide a forum for coordinating experimental and theoretical programs on large experimental devices, and to avoid unnecessary duplication of effort while still ensuring verification of important experimental or theoretical results.
- **Joint Research.** Through joint research, major facilities are made available for research projects of other programs. The facility is financed and constructed primarily by the host program, with other participating programs either providing a percentage of construction and operation costs or contributing equipment. In exchange for their contributions, participating programs are granted access to the machine and experimental data. Frequently, contributions of the participants enable an existing machine to be upgraded; in some cases these contributions are essential to the construction of the machine in the first place. Activities involving joint research are becoming increasingly common.
- **Joint Construction and Operation.** Joint construction and operation of major experiments and facilities are the most intensive forms of international cooperation; this form of cooperation is referred to as collaboration. Participating programs agree to pool their resources and construct a commonly owned and operated facility. There is no "host" program in this case; the facility is operated by a management team comprised of representatives from each program.

Plans for future U.S. participation in international fusion activities include collaborative projects in addition to the other levels of cooperation. The largest scale example of a collaborative project under discussion today would be a jointly constructed and operated engineering test reactor. The current proposal for this experiment, called the International Thermonuclear Experimental Reactor (ITER), involves only conceptual design and supporting R&D for the project. If this phase of the project is arranged and proves workable, more extensive collaboration on construction and operation could be considered.

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[3] A discussion of proposals for future cooperation and collaboration now under consideration can be found later in this chapter under "Prospects for International Cooperation."

[4] National Research Council, *Cooperation and Competition on the Path to Fusion Energy* (Washington, DC: National Academy Press, 1984), p. 5.

If successfully negotiated, ITER probably will be the world's largest, most expensive, and most visible cooperative project. Therefore, this chapter primarily focuses on it. The full scope of DOE's plans for future cooperative activity includes a variety of additional, lesser facilities in areas such as materials research and technology development. DOE plans to investigate more intensive forms of cooperation—including joint research, planning, and possibly even joint construction and operation of facilities—on these other projects as well. The U.S. plans for future cooperation are analyzed in this chapter under "Prospects for International Cooperation."

Types of Agreements

Different levels of international agreements could be used to facilitate cooperation. These agreements can range from formal treaties down to informal workshops and publications:

- **Treaty.** A treaty between governments is the most binding and formal agreement that can be established. Ratification signifies commitment to the substance of the agreement; obligations incurred under a treaty can be abrogated, but such action is not taken lightly or often. However, a treaty is the most difficult type of agreement to implement. There is a greater risk of negotiations breaking down during the development of a treaty, and more issues must be resolved in order for a treaty to be ratified. Moreover, the ratification process for a treaty is time-consuming; a treaty may be obsolete by the time it is finally ratified. In the United States, a treaty must be signed by the President and ratified by a two-thirds majority of the Senate.
- **Heads-of-State Agreement.** A heads-of-state agreement is less formal than a treaty but is considered binding by most governments. Such an agreement carries the full weight of the government in power, and abrogation by a signatory head of state would be an unusual, though not impossible, act. When the subject of the agreement has a strong base of support among many different groups, the risk that the signing head of state, or a succeeding one, would disavow the agreement is small.
- **Ministerial-Level Agreement.** A ministerial agreement is arranged between ministries of the participating governments, and it is less formal than either a treaty or a heads-of-state agreement. It requires less review and approval than the more formal agreements and is affected more directly by changes in budgetary constraints and political objectives. However, it still carries the full weight of the government. In the United States, ministerial-level agreements in fusion research are negotiated with participation of the Departments of Energy and State.
- **Informal Arrangement.** An informal arrangement can be undertaken between governments, laboratories, and individuals. It can provide an excellent means of transferring information among scientists, but it does not provide a basis for programmatic or international planning. This arrangement is typically instituted on an ad hoc basis, in response to particular needs and objectives of the participants.

Different types of agreements are appropriate for the various forms of cooperation that occur in fusion and in other areas (see table 7-1).

Most cooperative efforts occur under a general arrangement called an *umbrella agreement*. An

Table 7-1.—Comparison of Type of Cooperation and Level of Agreement

Type of cooperation	Level of agreement
Information exchange	Informal Arrangement Ministerial Agreement Heads-of-State Agreement
Personnel exchange	Informal arrangement Ministerial Agreement Heads-of-State Agreement
Joint planning	Ministerial Agreement Heads-of-State Agreement
Joint research	Ministerial Agreement Heads-of-State Agreement
Joint construction and operation	Ministerial Agreement Heads-of-State Agreement Treaty

SOURCE: Office of Technology Assessment, 1987

umbrella agreement usually is established as part of a ministerial agreement before any specific cooperative agreement is instituted. It defines the principles of cooperation and provides a framework for developing future cooperative agreements. It is undertaken when governments are interested in cooperation and want to formalize the intent to cooperate. An umbrella agreement typically states that the participating governments support cooperation and are ready to begin negotiating specific cooperative projects.

Frequently, an umbrella agreement authorizes transfer of preliminary information and technology, sets up joint planning and negotiation efforts, and provides a forum for exploring the potential of future cooperation on medium- and long-term projects. An umbrella agreement is not a final agreement. It is not intended to address the substantive issues involved in decisions to undertake specific cooperative projects. It is a useful device, however, for defining areas of potential cooperation and for creating a framework for negotiating future agreements.

MAJOR INTERNATIONAL AGREEMENTS

Under current arrangements, the United States participates in cooperative fusion activities at all levels except that of joint construction and operation. To date, only one international fusion project has been collaborative in this sense: the Joint European Torus project of the European Community (EC). Table 7-2 summarizes the principal existing international fusion arrangements; the organizations and agreements mentioned in the table are described below.

Multilateral Activities

International Atomic Energy Agency

The International Atomic Energy Agency (IAEA) has been one of the most important facilitators of fusion cooperation. The IAEA is an independent intergovernmental organization within the United Nations system, and its mission is to promote and ensure the peaceful use of atomic

Table 7-2.—Principal International Fusion Activities

Type of cooperation	Representative project	Agreement
Information exchange	Large Tokamak Agreement	IEA
	Nuclear Fusion journal	IAEA
	Conferences	IAEA
Personnel exchange	Large Tokamak Agreement	IEA
	50 transfers each way	U.S.-Japan Bilateral
	Six transfers each way	U.S.-USSR Bilateral
	To be determined	U.S.-EC Bilateral
Joint research	ASDEX Upgrade	IEA
	Large Coil Task	IEA
	Doublet III-D Upgrade	U.S.-Japan Bilateral
	Tore Supra	U.S.-EC Bilateral
Joint planning	INTOR	IAEA
	Large Tokamak Agreement	IEA
	Joint Institute for Fusion Theory	U.S.-Japan Bilateral
	To be determined	U.S.-EC Bilateral
Joint construction and operation	Joint European Torus	European Community

SOURCE: Office of Technology Assessment, 1987.

energy. The headquarters of the IAEA are located in Vienna, Austria. All countries currently doing fusion research are members of the IAEA. It has facilitated two different types of cooperative activity: information exchanges and joint planning efforts.

Major informational activities conducted by the IAEA in the area of fusion research include hosting biennial meetings and arranging topical meetings and workshops on areas of special interest or concern. In addition, the IAEA publishes a technical journal, *Nuclear Fusion*, in which fusion researchers can share their findings.

The IAEA also facilitates a joint planning activity, called the International Tokamak Reactor (INTOR) design study. INTOR began in 1978, and it involves the European Community, Japan, the Soviet Union, and the United States. The goal of INTOR is to define concepts and designs for a conceivable next-generation fusion experiment. It is a forum where Western fusion scientists have regular contact with their Soviet counterparts. National teams work on parallel tasks and meet two or three times a year for several weeks to compare results and plan future work. Most analysts agree that INTOR discussions have successfully identified critical issues in both physics and technology.

International Energy Agency

The International Energy Agency (IEA) was created by 21 Western oil-importing nations in 1974 in response to the OPEC oil embargo. IEA's main task is to plan for crisis response to future oil embargoes. In addition, the IEA also promotes international cooperation in research and development of energy technologies that have the potential to decrease the West's dependence on oil imports. The European Community, Japan, and the United States participate in IEA's cooperative projects. Magnetic fusion research is one of many areas IEA promotes, largely by facilitating joint research efforts. The IEA is headquartered in Paris, France.

In 1977, the Large Coil Task (LCT) was organized under the auspices of the IEA. As part of the LCT, the U.S. fusion program constructed the International Fusion Superconducting Magnet Test Facility at Oak Ridge National Laboratory in Tennessee at a cost of about $40 million. This facility is designed to test superconducting magnet coils.[5] It holds six large coils, one each constructed by the European Atomic Energy Community, the Japan Atomic Energy Research Institute, and the Swiss Institute for Nuclear Research and three constructed by U.S. manufacturers.[6] Each coil cost between $12 million and $15 million to construct. International involvement in the LCT has distributed the costs of the project among several nations, and it has also enabled different types of coils to be tested in a common facility, allowing direct comparison. Moreover, the LCT is the major instance in the fusion area that involved industry in international cooperation.

Several other cooperative projects also occur under IEA auspices. The European Community and the United States participate in joint planning on next-generation stellarator experiments to coordinate their research efforts. It appears that Japan will soon be joining this project. Through the IEA, the United States and the European Community are also conducting joint research on the Axisymmetric Divertor Experiment (ASDEX) and its upgrade (ASDEX-U). These facilities are located at the Institute for Plasma Physics at Garching, Federal Republic of Germany, and U.S. participation in this research has made it unnecessary for the United States to construct similar facilities. The IEA provides no funding for any of these projects, only an umbrella framework and minor secretariat functions.

The most recent IEA agreement, signed in January 1986, provides for cooperation among the three large operational tokamak experiments (JT-60 in Japan, the Joint European Torus (JET) in the European Community, and the Tokamak Fusion Test Reactor (TFTR) in the United States). Under this agreement, the three programs conduct personnel and information exchanges for tokamak experiments. An executive committee, consisting of two members from each fusion program,

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[5] For a discussion of the role of superconducting magnets in a fusion reactor, see the section of ch. 4 titled "The Magnets" under "Fusion Power Core Systems."

[6] U.S. Department of Energy, Office of Energy Research, *Magnetic Fusion Energy Research: A Summary of Accomplishments*, DOE/ER-0297, December 1986, p. 19.

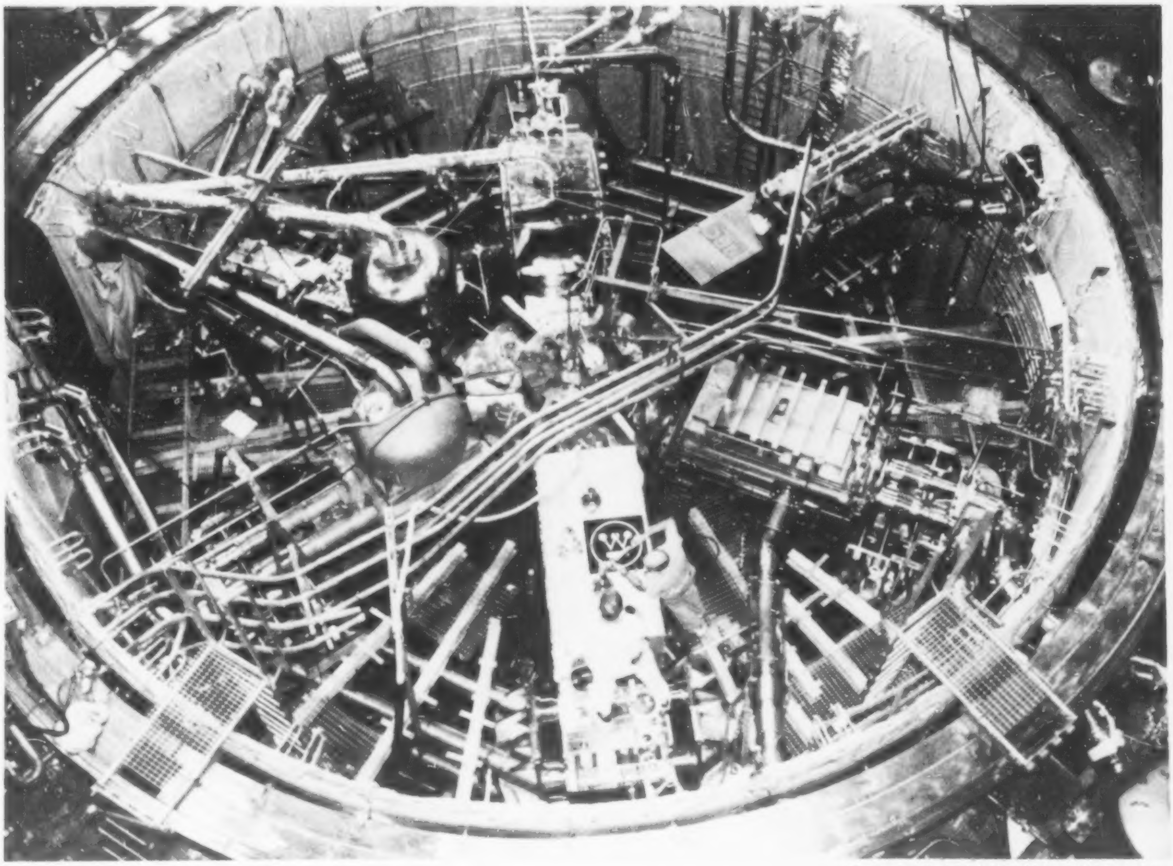

Photo credit: Oak Ridge National Laboratory

The International Fusion Superconducting Magnet Test Facility at Oak Ridge National Laboratory, containing the six superconducting magnets.

will meet at least once a year to coordinate research. The agreement is in effect from 1986 to 1991. This agreement has the potential to evolve into joint planning and program coordination.

Joint European Torus

The Joint European Torus is Europe's most important experimental fusion facility and the world's largest tokamak. JET is a joint undertaking of the member nations of the European Community; it has been designed, constructed, and operated by the EC. The JET Working Group was created to explore the project in 1971; the device was approved by the EC Council of Ministers in 1978, following a political wrangle of 2½ years over project location.

The JET experiment is located adjacent to the Culham Laboratory, in Abingdon, United Kingdom. The land on which JET is constructed is temporarily leased from the United Kingdom; at the completion of the project the land will be returned. Construction of JET began in 1977, and the facility began operating in 1983; current plans call for JET to operate until about 1992.[7]

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[7] For an account of the design phase and the political negotiations concerning JET, see Denis Willson, *A European Experiment: The Launching of the JET Project* (Bristol, U.K.: Adam Hilger Ltd., 1981).

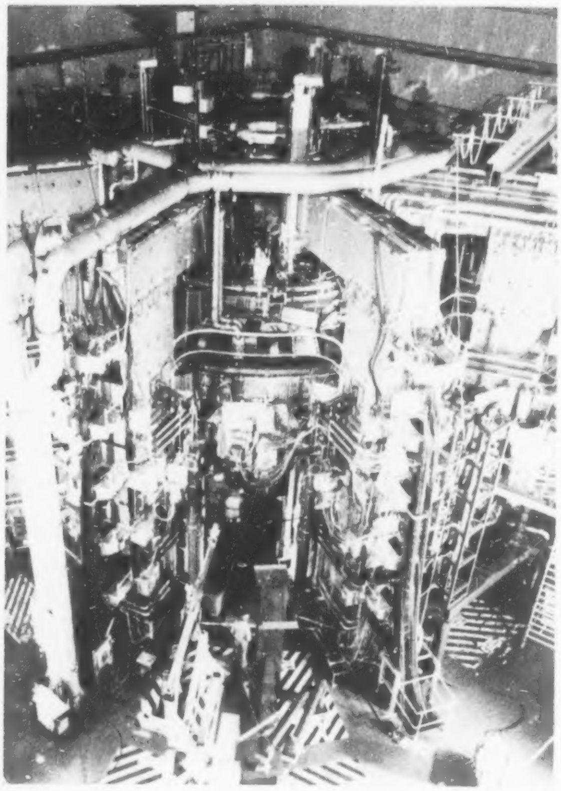

Photo credit: JET Joint Undertaking

The Joint European Torus, located in Abingdon, United Kingdom.

Legally, JET is an independent international entity; it is not a national project. The JET administrative structure is multinational. The project is managed by a project director on site, but all important strategic decisions must be presented to and approved by the JET Council, which is comprised of two members from each participating nation, one of which is a scientist. When the project is completed, the administrative structure will be dismantled.

JET is staffed by two distinct and roughly equal-sized groups: the multinational staff supported by the EC and a local staff supported by the United Kingdom Atomic Energy Agency. Provisions have been made for staff to return to their national fusion programs after completion of their appointments at JET.

The EC pays 80 percent of the costs of JET through the contributions of member nations. In addition to their contributions through the EC, the national programs also contribute directly to the project. Direct national contributions represent 10 percent of the costs. The final 10 percent is a site premium paid by the United Kingdom. This premium offsets the financial benefits that the host country receives from the project. In the last 5-year budget plan, approved in 1985, funding for the overall EC fusion program for 1985-89 was set at 690 million European Currency Units (worth at that time about $766 million). Of this amount, roughly half will go to JET.

The JET model has been effective and efficient. Through cooperating on the project, national programs have saved money, have had access to a world-class experiment, and have advanced the state of European scientific research.

Bilateral Activities

United States-Japan Bilateral Agreement

In 1979, a ministerial-level agreement was signed committing the United States and Japan to cooperate on general energy research and, more specifically, to develop commercial fusion power for the 21st century. Within the framework of this umbrella agreement, the United States and Japan have negotiated several specific cooperative agreements. The U.S.-Japan cooperation is the most extensive international cooperation in fusion research in which the United States participates. Information and personnel exchanges, joint research activities, and joint planning activities all occur within the context of the umbrella agreement.

About 50 formal personnel exchanges occur each way annually between the United States and Japan.[8] There are also a few (usually under 10) personnel exchanges arranged yearly on an ad hoc basis; these informal exchanges enable the partners to accommodate unique program needs.

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[8] Michael Roberts, Director of International Programs, U.S. Department of Energy, Office of Fusion Energy, letter to the Office of Technology Assessment, Aug. 6, 1986.

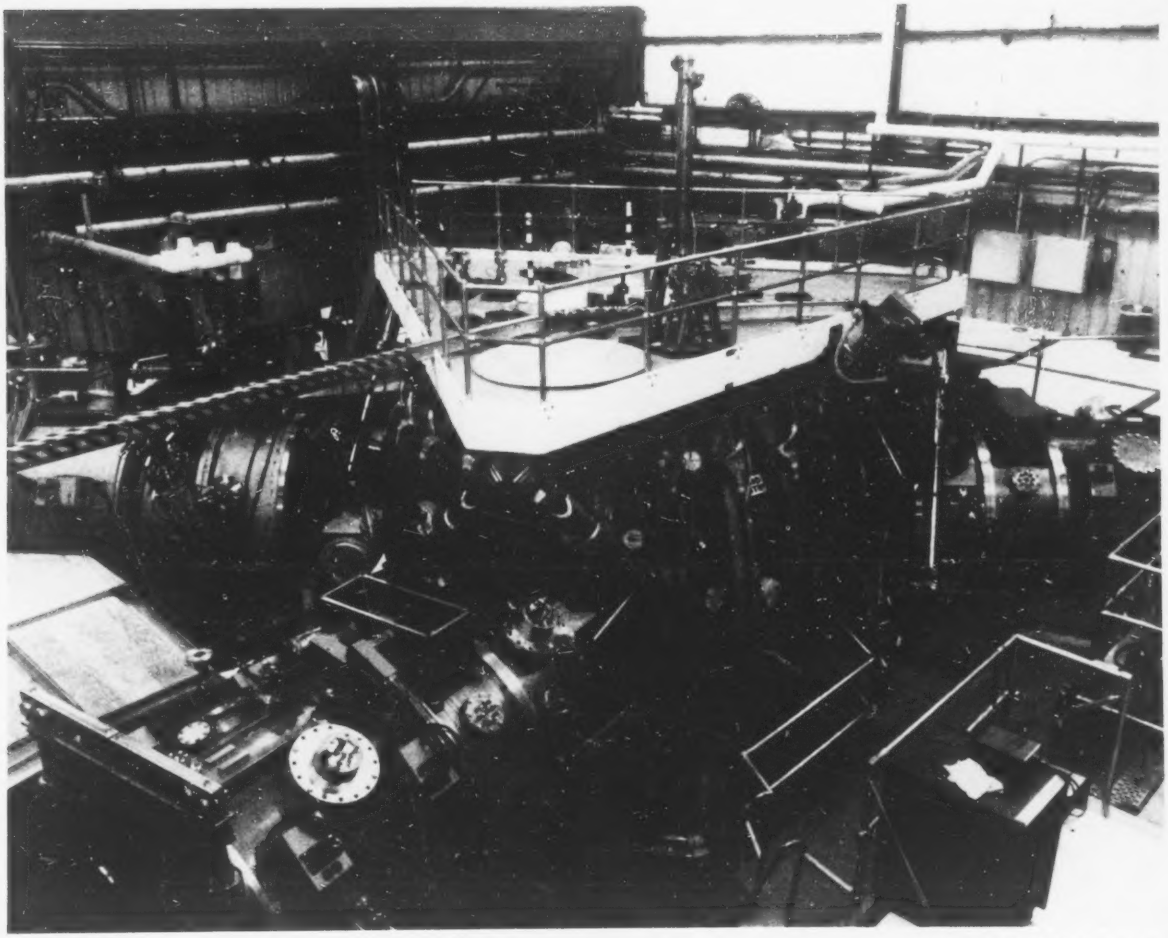

Photo credit: GA Technologies, Inc.

D III-D fusion device at GA Technologies, San Diego, California, showing neutral beam injection systems.

Under the umbrella agreement, a specific agreement to conduct a major joint research project was also signed in 1979. Through this agreement, Japanese involvement in the upgrade of the U.S. Doublet III (D III) tokamak was formalized.[9] The Japanese and the Americans shared machine time on the experiment equally, and both have had access to all data generated in the experiments run on the machine.

The United States hosts the Doublet project, which is located at GA Technologies' laboratory in California. Since 1979 the project has had joint funding and a joint management team. Between 1979 and 1984, the United States contributed $104 million and the Japanese contributed $62 million to finance an upgrade in the D III facility (after the upgrade the name was changed to D III-D). In 1983, the agreement was extended until 1988, and additional upgrades were undertaken for which the United States is contributing $37.8 million and Japan $8.5 million. Currently, discussions are underway to extend cooperation until 1992.[10]

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[9] U.S. Department of Energy, *Magnetic Fusion Energy Research*, op. cit., p. 20.

The Doublet cooperation has provided both parties with access to a state-of-the-art tokamak for much less than the cost of independently constructing and operating the experiment. In fact, it is unlikely that the D III upgrades would have been possible without Japanese funding contributions. In addition, Japanese and U.S. scientists both have made valuable technical contributions to the experiment that have improved the scientific quality of the project.

Within the context of the U.S.-Japan umbrella agreement, the countries also have undertaken joint planning activities. The United States and Japan have created a Joint Institute for Fusion Theory (JIFT) and designated two theory centers, one at the University of Texas at Austin and the other at Hiroshima University in Hiroshima, Japan. Each fusion center has continued to operate independently, and a coordinating committee has been created to oversee and guide cooperative activities.

United States-U.S.S.R. Bilateral Agreement

The Soviet Union has cooperated extensively with the United States and has made substantial contributions to the U.S. fusion program (see the history of tokamak development in ch. 3). The United States and the Soviet Union have had a formal agreement to cooperate in fusion research since 1958. In 1973, this agreement was strengthened, under the Nixon-Brezhnev Accord, to extend and broaden cooperation in fusion research. Most of the detailed information that the U.S. fusion program has about the Soviet program comes from the U.S.-Soviet exchange activities.[11]

Under the terms of the Nixon-Brezhnev Accord, 12 personnel exchanges occur between the United States and the Soviet Union annually, six in each direction. These exchanges are limited by the United States to fusion science issues, such as experiments and theory, with no regular interaction on technology development.[12] Most of the personnel exchanges are visits; some are assignments, however, which have given Soviet scientists an opportunity to work with U.S. scientists on research projects, and vice versa.

The U.S.-U.S.S.R. bilateral agreement is vulnerable to the political situation between the two countries. For example, no exchanges occurred during 1980 or 1981, the years following the Soviet invasion of Afghanistan. However, since the 1985 U.S.-U.S.S.R. summit meeting in Geneva, bilateral activity between the nations has progressed to a point where collaboration with the Soviet Union on the conceptual design and supporting R&D of a major fusion experiment is being considered.[13]

United States-European Community Bilateral Agreement

The United States and the European Community have cooperated extensively for more than 30 years without a formal bilateral agreement. Until recently, most cooperation involving the EC and its member states was conducted indirectly through the IEA. While this cooperation was rewarding, many tasks were not easy to arrange under the existing arrangements.

A ministerial agreement was signed between the United States and the EC in December 1986. Because the agreement was signed so recently, details for all of the activities that will occur within its framework have not yet been formalized. Arrangements have been made for joint research at the JET facility in the United Kingdom and at the Tore Supra facility in France. The agreement will provide an annual forum for management discussions about bilateral cooperation issues and will establish a legal basis that can simplify the exchange of hardware and the initiation of some cooperative endeavors. It also will increase the mobility of European scientists; within the EC, a formal agreement helps facilitate personnel exchanges.

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[10] *Testimony of Dr. David Overskei*, Senior Vice President at GA Technologies, Inc., before the House Science, Space, and Technology Committee, Energy Research and Production Subcommittee on the Fiscal Year 1988 Magnetic Fusion Energy Budget, Feb. 24, 1987, p. 4.

[11] U.S. Department of Energy, Office of Fusion Energy, *Evaluation of Benefits of Cooperation on Magnetic Fusion Energy Between the United States and the Soviet Union for the period 1983 to 1985*, November 1985.

[12] Ibid., app. A.

[13] The Geneva summit meeting and the subsequent proposal for a major fusion collaboration involving the Soviet Union are discussed on p. 184.

EVALUATION OF COLLABORATION

Benefits and Risks

Knowledge Sharing

All forms of international cooperation involve information transfer. Throughout the history of fusion research, access to information—including technical know-how, experimental data, and new theoretical ideas—has enabled fusion scientists to learn from each other. Innovative ideas and a wider variety of approaches to projects are more likely to arise in an international versus a purely domestic program.[14] Researchers can compare their experimental results with those of other programs, making it possible to verify results, identify anomalous data, and distinguish experimental results based on fundamental characteristics from results based on special features or flaws in a particular experimental device. Thus, scientific progress can occur more rapidly through cooperation.

On the other hand, some observers feel that extensive knowledge sharing between national fusion programs should be discouraged in the interests of national security and national competitiveness. These individuals believe that the advantages of information transfer, in terms of improved scientific research, do not outweigh the disadvantages of participating in extensive cooperative projects.

Cost Sharing

One advantage of international cooperation is that it potentially can save significant amounts of money. Information and personnel exchanges enable independent programs to learn, at low cost, about the research activities of other programs. Joint planning activities enable fusion programs to coordinate activities to avoid duplication of effort and to conduct mutually beneficial research. Most dramatically, joint research and joint construction and operation of projects distribute the costs of major experimental facilities, while still providing the experimental results to all participants.

The full extent of the cost savings is unclear, however. As the National Research Council report pointed out, because cooperation requires extensive negotiation and more formal management structures, the total administrative costs of constructing and operating a cooperative project are higher than if the same project were constructed independently.[15] Moreover, there are additional costs if the facility is not sited in the United States, such as lost domestic contracts, employment, and support facilities.[16] Although these added costs temper the financial benefits of international cooperation, it is expected that the contribution of any one partner will be less than the cost of that partner proceeding independently with an identical project.

Risk Sharing

International cooperation on major experimental facilities can mitigate the risk of project failure by spreading the financial and programmatic costs over all participants. Constructing and operating large experimental facilities is expensive; the cost of failure, both monetarily and on a program's morale and future plans, can be high. Through sharing knowledge between major fusion programs, there is a greater probability of scientific or technical success. In addition, the formal agreements required to negotiate an international project and the political implications of abandoning such an undertaking may serve to stabilize national commitments to the project.

On the other hand, some scientists feel that the absence of competition and duplication among experimental facilities may increase technical risk and that extensive cooperation may increase the risk of abandonment before project completion. Some members of the fusion community point out that coordinating research to the point of jointly constructing a single international facility, as opposed to comparable national facilities, would eliminate the potential for validating experimental results through comparisons between different machines of similar size and purpose. With more than one machine, a number of different scientific and technical approaches could be explored, and experimental results among machines could be compared. In addition, some feel that the absence of competition among facilities will lead to more conservatism in design and operation, which can limit progress. Finally, all participants must fulfill their financial and personnel obligations if the project is to succeed, especially with larger, more complex projects that extend over several years. The entire project can be jeopardized if even one nation abrogates the agreement, and cancellation can have implications far broader than just one abandoned project.[17]

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[14] See U.S. Department of Energy, Office of Energy Research, *International Program Activities in Magnetic Fusion Energy*, DOE/ER-0258, March 1986, p. 5; or National Research Council, *Cooperation and Competition*, op. cit., p. 19.

[15] National Research Council, *Cooperation and Competition*, op. cit., p. 31. Actual statistics are difficult to collect; however, one survey of technical personnel involved in the INTOR workshop indicated that constructing INTOR as an international project would increase total costs by about 70 percent, staffing requirements by 15 percent, and require 2 years longer to complete. It is not clear that these projections are generally applicable; cooperative construction of JET probably did not inflate costs this much. However, no matter to what degree, collaboration will tend to increase construction times and project costs.

[16] Testimony of Dr. Walter A. McDougall, Associate Professor of History at the University of California—Berkeley, *Science Policy Study Volume 7: International Cooperation in Science*, Hearing before the Task Force on Science Policy of the Committee on Science and Technology, House of Representatives, 99th Cong., 1st sess., June 18-20 and 27, 1985, p. 70.

Diplomatic and Political Implications

A large cooperative experiment will clearly have significant diplomatic and political implications. Many proponents of international cooperation believe the diplomatic and political consequences can be positive. The commitment to cooperate on an experimental fusion device is not trivial; a commitment represents confidence in the reliability of the other participants and faith that they can work together to the benefit of all involved. Through the negotiating process, differences between partners can be reconciled and a commitment to a common goal can be affirmed.

In addition, the diplomatic value of a decision to cooperate could be used to further U.S. objectives and improve U.S. relations in areas otherwise unrelated to fusion. For example, an agreement to cooperate on magnetic fusion could be reached as part of a larger non-technical diplomatic initiative. Some observers argue that such diplomatic benefits have been particularly valuable in the case of U.S.-Soviet cooperation, and that more intensive cooperation with the Soviets should be pursued.

Some people consider these non-technical diplomatic benefits a positive feature of large-scale cooperative projects. Others, however, fear that the diplomatic implications of collaboration could result in the subordination of technical objectives to non-technical goals, which would be undesirable. Moreover, some observers fear that international projects should be viewed cautiously because broken cooperative agreements could complicate international relations. If a nation abandoned its commitment in the course of a cooperative undertaking, there could be important political consequences. The fear of these consequences might even cause reluctance to terminate a technically undesirable project.

Domestic Implications

In addition to its technical benefits, many proponents of cooperation support it as a method of preserving the U.S. fusion program. These individuals are concerned, at least in part, that current budgets are insufficient to maintain a viable domestic fusion effort. At current funding levels and as currently structured, the U.S. fusion program cannot construct and operate essential experimental facilities on its own without dramatic curtailment of other necessary aspects of the fusion effort. Collaboration proponents therefore see intensive international cooperation as critical for a challenging, growing U.S. research program. This point is made in the National Research Council report:

> For the United States at this time, large-scale international collaboration is preferable to a mainly domestic program which would have to command substantial additional resources for the competitive pursuit of fusion energy development or run the risk of forfeiture of equality with other world programs.[18]

Increased international cooperation in fusion energy research can also stabilize the commitment of the U.S Government to the magnetic fusion program.[19] Moreover, international projects often have more visibility than domestic undertakings and therefore can better mobilize public support.

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[17] National Research Council, *Cooperation and Competition*, op. cit., p. 23.

[18] Ibid., p. 11.

[19] Ibid., p. 22.

However, incentives for future collaboration on big fusion projects must be traded off against a variety of other domestic concerns. Some members of the fusion community, for example, worry that the United States might link the continued viability of its fusion program to international activities that it cannot adequately influence.[20] Others are concerned that U.S. policymakers might sacrifice the Nation's domestic fusion program in order to promote international cooperation,[21] particularly if domestic budgets were not increased sufficiently to cover the additional cost of an expensive cooperative project. In addition, some individuals are concerned that undesirable changes in the direction of fusion research might be made to facilitate increased cooperation. Finally, there is concern that the participation of domestic universities and industry in fusion research could be limited if the program emphasizes international cooperation.

Obstacles[22]

A number of potential obstacles must be addressed through negotiation before the United States can participate in large-scale cooperative projects in fusion research.

Technology Transfer

Transferring high technology to our partners could be the most serious political obstacle to more intensive international cooperation. Many critics worry that militarily significant technology could be transferred, either directly or indirectly, to the Soviet Union through fusion cooperation, especially through joint construction and operation projects. Some analysts are also concerned that cooperation in fusion could jeopardize U.S. competitiveness in international markets.

National Security.—Some of the technologies developed for use in fusion experiments—e.g., high-power neutral beams, high-power microwave technology, and plasma diagnostics—can, with varying degrees of modification, have military applications. Various individuals and government agencies contend that the Soviet Union will be able to utilize technology transferred through more extensive fusion cooperation for military applications. According to Richard Perle, former Assistant Secretary of Defense for International Security Policy, "Soviet officials and agents have successfully exploited the openness of the U.S. and European scientific communities to gather militarily useful technical information."[23] Opponents of extensive cooperation with the Soviets contend that it would be difficult, if not impossible, to control the transfer of militarily sensitive technology in an experimental facility such as ITER. In particular, opponents contend that long-term association with Western scientists will provide disproportionate benefits to the Soviets. Opponents say that through the ITER project, Soviet scientists will be able to acquire Western know-how, technology, and experience in leading-edge technologies.

Supporters of cooperation do not claim that military applications of fusion-related technologies are irrelevant, but they believe that many of the concerns raised by opponents are overstated. When examined in detail, proponents argue, most of the objections disappear, and those that remain can be addressed on a case-by-case basis. As the Director of the Office of Energy Research at DOE has stated:

> It is my opinion . . . that a device of the sort we are talking about could be built and that the necessary computer activities associated with it could be carried out in a manner that did not involve any violation to COCOM regulations.[24]

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[20] Ibid.

[21] Ibid., p. 23.

[22] The information in this section is based on a workshop on Issues in International Cooperation held by the Office of Technology Assessment, Washington, DC, on Oct. 14, 1986 (list of panelists presented in front of this report); on reports done under contract to OTA by specialists in Japan, Europe, and the Soviet Union; on discussions and interviews conducted with members of the fusion community; and on the National Research Council report *Cooperation and Competition*, op. cit.

[23] Richard Perle, Assistant Secretary of Defense for International Security Policy, "Technology Security, National Security, and U.S. Competitiveness," *Issues in Science and Technology*, fall 1986, vol. III, No. 1, p. 112.

[24] Testimony of Alvin W. Trivelpiece, Director of the Office of Energy Research, U.S. Department of Energy, *Fiscal Year 1987 De-*

Proponents point out that, generally, fusion technologies are not directly applicable to military needs; those technologies that do have defense applications must undergo substantial modification and redesign before reaching military significance. For example, although many of the technologies currently being investigated in the Strategic Defense Initiative were first developed for or used by the magnetic or inertial fusion programs, U.S. scientists are nevertheless spending billions of dollars to apply these technologies to weapons systems. Applying fusion technologies to military uses may require as much indigenous technical capability as developing the technologies in the first place.

Furthermore, supporters of U.S.-Soviet fusion collaboration argue that those technologies posing true risks can be identified through careful review procedures and that problems can be handled on a case-by-case basis. If, for example, a particular component poses a significant technology transfer risk, the Soviets could be asked to provide it, its use could be restricted, or the experiment could be redesigned to eliminate it.

Proponents of increased cooperation insist that there are significant benefits to the United States from collaborating with the Soviet Union that must be weighed against the risks. Magnetic fusion research is not classified; information about experiments, techniques, and methodologies are available in international publications. Moreover, as the Associate Director of Confinement at Oak Ridge National Laboratory noted:

> Everything in the world is not done here. In many areas we are not ahead . . . We got the fact that you could make a gyrotron [a high-power microwave generator] from the Russians. All sorts of things came out of the Russian program.[25]

Over the years, the Soviet Union has made valuable contributions to fusion research, and its participation in a major project would improve the quality of the undertaking.

Undoubtedly, measures taken to resolve technology transfer concerns will constrain the free flow of information and technology between the partners in collaboration. Such constraints may pose an obstacle to collaboration in their own right: it is possible that after compromises have been made to satisfy technology transfer concerns, the proposed collaborative project might not satisfy the needs of the parties in the activity, including the U.S. fusion community. If, for example, it was decided that the use of old technology would avoid the risk of transferring state-of-the-art technology, the overall capabilities of the device could be reduced, and as a result the project could become less attractive.

The national security debate is not easily resolved, and it involves underlying motivations and assumptions concerning the U.S.-Soviet relationship that go far beyond the details of any specific technical exchange. Given the depth of the debate within the U.S. Government, it appears that the United States will not be able to participate in a major joint undertaking with the Soviet Union until these issues are settled. Many observers contend that resolving the national security questions ultimately will require a Presidential decision.

U.S. Competitiveness.—Many analysts are concerned about the competitiveness of American industry in international markets, and some are hesitant, in particular, about the long-term implications of intensive cooperation with the Japanese and the Europeans in fusion.[26] At present, U.S. industry is only minimally involved in the fusion program. If no provisions are made to directly involve U.S. industry in future collaborative projects such as ITER, some observers fear that U.S. industry could fall farther behind Japanese industry—particularly since Japanese industry is more directly involved in fusion research.[27]

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partment of Energy Authorization: Magnetic Fusion Energy, Hearings before the Subcommittee on Energy Research and Production, Committee on Science and Technology, House of Representatives, 99th Cong., 2d sess., Feb. 25-26, 1986, p. 24.

COCOM is the acronym of the Coordinating Committee, an informal, voluntary, cooperative alliance through which the United States and its allies seek to control the export of strategic goods and technology to the Eastern bloc. It is an intergovernmental committee, and 15 nations participate in it—the NATO countries (except for Iceland and Spain) and Japan. Members of COCOM have agreed to restrict export of certain specified items to Communist countries for strategic reasons.

[25] Mark Crawford, "Soviet-U.S. Fusion Pact Divides Administration," *Science*, May 23, 1986, p. 926, quoting John Sheffield, Associate Director of Confinement at Oak Ridge National Laboratory.

[26] The General Accounting Office documents this concern in its report *The Impact of International Cooperation in DOE's Magnetic Confinement Fusion Program*, report to the Honorable Fortney H. Stark, Jr., House of Representatives, GAO/RCED-84-74, February 1984, pp. 13-14.

[27] For a more detailed discussion of industrial participation in the U.S. fusion program, see the section in ch. 6 titled "Private Industry."

DOE does not consider U.S. competitiveness issues to pose a serious obstacle to increased cooperation in fusion. As DOE points out, magnetic fusion is currently in a pre-competitive stage. Because there are few commercial applications of the technology, there are no substantial risks from sharing the technology internationally. According to DOE, there appears to be little risk that the United States would sacrifice its future competitive position through near-term cooperative endeavors.

Technical Differences

Successful cooperation on a major device like ITER requires that the partners agree on a common set of goals and objectives, that their fusion programs be at comparable levels, and that they be moving in compatible directions. Differences between the long-term objectives of the partners' fusion programs or research plans must be accommodated or resolved.

At present, all the major world fusion programs agree on the need for an experiment such as ITER and welcome it as an opportunity for more intensive cooperation. However, given the differences in detailed technical objectives among the programs, designing an experiment that satisfies each program's goals simultaneously will involve a great deal of negotiation and compromise.

Project Location

Siting major projects, whether domestically or internationally, is traditionally time-consuming and politically sensitive. According to the National Research Council, selecting a project site is a "frequent sticking point in large international projects."[28] Intense competition for the site of a major international fusion project can be expected, since such a facility will be beneficial to local institutions, may provide some advantage to local industry, and will carry a great deal of prestige.

Most analysts believe it is unlikely that the facility will be located in either the United States or the Soviet Union. It is not expected that either nation would participate if the project were located within the other's borders. In addition, with both the Western Europeans and the Japanese sensitive about superpower dominance, they too might be reluctant to site the project in either the United States or the Soviet Union.

Even after the competition is narrowed down to one nation or region, internal competition for the site will be intense. In the case of the JET project, for example, the siting negotiations took over 2½ years to resolve and almost caused the abandonment of the project.[29] The siting decision for ITER probably will be even more difficult, since it will be a larger facility and more nations will be involved. Collaboration on ITER requires that the project have value to all participants, including those that do not host it.

U.S. Commitment

Another difficulty for U.S. participation in a major international joint undertaking is the degree of commitment by the U.S. Government to the fusion program. The U.S. fusion program has faced decreasing budgets, in real terms, for 9 of the last 10 years, and, given this recent history, international partners could reasonably question U.S. commitment to the development of fusion energy. Moreover, many nations already believe that cooperating with the United States is risky. A recent Energy Research Advisory Board panel on DOE's international research and development activities concluded:

> . . . the Department [of Energy] has a poor reputation abroad for long-term commitment to international collaborative programs. This poor reputation will make it extremely difficult for DOE to attract foreign countries into significant new partnerships . . . the responsibility lies with DOE to improve its own image abroad.[30]

The United States needs to establish a strong and stable commitment to its domestic fusion program as well as to international projects in order to win the confidence of potential partners.

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[28] National Research Council, *Cooperation and Competition*, op. cit., p. 57.

[29] Denis Willson, *A European Experiment: The Launching of the JET Project*, op. cit.

[30] Energy Research Advisory Board, *International Collaboration in the U.S. Department of Energy's Research and Development Programs*, op. cit., p. 2.

Equitable Allocation of Benefits

Negotiating an agreement in which the benefits of the project are distributed equitably in relation to the investment of the participants will be complex. Among the benefits are the distribution of available staff positions, the amount of design and equipment fabrication work to be done by contractors, and the access or rights to information and technical know-how generated by the project. Benefits associated with hosting the site of the experiment also must be accounted for, a task that has frequently resulted in requiring the host to contribute more to the project's costs. In the JET project, for example, the United Kingdom contributes 10 percent of project costs as a site premium, over and above its contribution as a participant.

Administration

For cooperation to be successful, it will be necessary to resolve a variety of administrative issues faced in all cooperative programs.

Different Institutional Frameworks.—Each national agency involved in negotiations operates under different rules and procedures. In addition, the negotiating agencies generally have varying degrees of autonomy, flexibility, and decision-making power.

Decentralization of the U.S. Government.—The decentralized character of the U.S. Government poses a challenge to developing major international agreements. Each executive branch agency has different concerns, making it difficult for the U.S. Government to reach the consensus needed to "speak with one voice." Therefore, negotiators will have to ensure either that there is widespread commitment to the project within the U.S. Government or that the project has support at levels of government high enough to assure such a commitment.

Different Budget Cycles.—Agreements will have to reconcile differences in national budget-setting procedures in order to finance a major cooperative undertaking. The European Community, for example, has a multi-year budget cycle, whereas both the United States and Japan have annual budget cycles. Even these annual budget processes are quite different. Whereas the Japanese budget process is very incremental, with major changes in program funding levels being unusual, in the United States the budget cycle is less stable and less predictable. Funding choices are reevaluated annually in the United States, and changes in priorities are common. Thus, there is some concern that the United States might make a commitment to begin a long-term project and then change its mind.

It has been suggested that the United States adopt a multi-year budget cycle or take major international projects "off-budget." While such actions certainly would reduce the budgetary obstacles to cooperation, the chance of such a change is slim, because the ramifications of such a decision would extend far beyond any particular project.

Different Currencies and Economic Systems.—It is generally considered easier if international project management minimizes currency transfers between nations. Different budget cycles, fluctuating exchange rates, and different economic systems—particularly with regard to the Soviet Union—make limiting the exchange of currency an attractive goal. Therefore, having participants contribute components and services is preferable to having them contribute funds to a central management agency that contracts for construction of necessary components.

Different Legal Systems.—Nations also have different legal systems that can complicate negotiations. Defining legal ownership of the experimental facility and of the information generated there is a critical facet of a workable agreement.

Personnel Needs.—The staff of a joint undertaking will include participants from all programs involved in the project, and administrative arrangements will have to accommodate their needs. Currently, relationships between staff and their respective governments differ over such issues as the ability to sign contracts, intellectual property rights, and compensation.

Staff for the project would come to a central location from many countries and would in most cases bring their families. They would expect, without undue difficulty, to find housing with access to shopping facilities and other amenities.

In particular, they would want an international, rather than national, educational system for their children. Moreover, most staff will return to their home fusion programs after completion of their assignments at the joint facility, and they will need to be assured that their positions at home will remain available to them.

Management Approaches

If the conceptual design phase of the ITER project is successful, it could be followed by a decision to jointly construct and operate a major fusion experiment. The prospects for such an activity are being investigated by the major fusion programs. Any agreement to undertake such a project would be complex, and a variety of management and organizational issues could arise in project negotiation and implementation. This section explores the applicability of management structures developed for existing international projects, both in fusion and in other areas, to the potential collaborative fusion endeavor.

The organizational structure of a large-scale international project such as ITER depends on its overall goals and objectives, which will be determined through negotiation. The main requirement for the organizational structure is that it define each participants' degree of control over the project by establishing such things as the project's technical and political decisionmaking procedures, the allocation of contributions and benefits among the partners, the degree of autonomy between the collaborative project and the supporting domestic fusion programs, the arrangements for staff and contractors, and the routine operation and long-range planning of the enterprise.

The degree of control that any participant exerts over the direction of the project can vary significantly, from minor technical influence to oversight of the entire project. Generally, however, the amount of control a partner exercises is proportional to the amount of financial support it provides. **In the case of ITER, it appears likely that financial support will be fairly evenly divided among partners; thus, project control probably will be shared by the partners.**

The management structures of the existing cooperative projects examined below offer some insight into how—or how not—to organize fusion collaboration. Since each project's goals are different, it is unlikely that any of these existing arrangements will be applicable as is for future fusion collaboration. Each project weighs its goals and requirements independently, and, through negotiation, unique trade-offs among competing goals are made. Studying the organizational structures of existing international projects, however, can be useful in exploring future projects such as ITER.

International Tokamak Workshop (INTOR)[31]

Conducted under IAEA auspices, the INTOR design study for a next-generation fusion experiment has features that may be useful for future collaborative projects. INTOR has successfully enabled the international fusion programs to cooperatively develop a design for and explore the technical characteristics of a next-generation machine. Moreover, the INTOR process was developed without causing concerns about national security and is the most extensive cooperative fusion activity involving the Soviet Union. Since INTOR is strictly a design effort, however, it provides no guidance for the construction and operation of future fusion collaborative experiments.

Joint European Torus (JET)[32]

The JET management structure is another approach for major collaborative projects. The JET facility was designed and built by multinational teams, is financed by the EC and the participating national fusion programs, and is managed by a multinational council. The project has been successful, and the EC currently is exploring the possibility of using the same approach to manage a next-generation experiment (the Next European Torus or NET).

Though the JET approach has proven successful for European fusion collaboration, it is not directly applicable as a model for ITER. First, the

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[31] The INTOR project is discussed in more detail on p. 159.

[32] See pp. 160-161 for a detailed description of JET.

JET agreement was negotiated within the existing umbrella structure of the European Community in which most of the administrative obstacles to international collaboration were already resolved. Negotiating a major fusion cooperation that included parties outside of the EC would be significantly more complex because there is no previously negotiated legal framework.

In addition, the JET approach was not designed to provide a mechanism for limiting the transfer of potentially sensitive technologies. Within the JET framework, all participants have access to the information and technology used or developed in the project. Finally, the JET structure operates through the cash contributions of participating programs to its central management agency. Hard currency transfers among the participants in an ITER-type project would be more difficult to arrange.

Large Coil Task (LCT)[33]

The Large Coil Task is a superconducting magnet testing project that has been conducted under the auspices of the IEA. The United States has taken the lead on the project, financing construction of the magnet testing facility and three of the six test magnets. The facility was designed jointly, and three magnets were designed, constructed, and financed by foreign participants in the project. All information and non-proprietary technology used in construction of the test magnets and all data generated through the experiment are available to participating programs.

Although the LCT was not designed to preclude information and technology transfer, its structure could be slightly modified and used if limiting such transfer was an objective. If a given task were broken down into distinct components, each subtask could be assigned to a partner who would be responsible both financially and technically for its contribution. Provided that the "independent development" met technical specifications, each partner's contribution could be integrated into the overall machine, minimizing exchange of information.

This approach might resolve technology transfer concerns, but it could also introduce considerable difficulties into project management. Since a primary goal of collaborating on a next-generation fusion experiment would be to make experimental techniques and results available to all the cooperating parties, the independent development approach probably would not be acceptable in ITER. In addition, it would be difficult to divide a major fusion project into isolated modules connected at interfaces; ITER probably will be a complex and interrelated assemblage of systems and components. Moreover, coordinating a project in which data and access were restricted would require an extremely effective management team.

Another problem with applying the LCT model to a future collaboration like ITER is control of the project. In the LCT, the United States contributed most of the financial support and assumed principal technical control. For ITER, on the other hand, it appears unlikely that any partner will assume the responsibility of becoming project leader and shouldering most of the cost. Thus, the management design of the LCT will not be applicable to ITER.

Doublet III Project (D III)[34]

Doublet III is the most extensive cooperative fusion project in which the United States currently is involved. The United States is the host country for the Doublet project, and the Japanese have contributed over one-third of the funds necessary to support the project in recent years. This direct contribution of currency distinguishes the Doublet cooperation from other fusion activities in which the United States participates. The project is jointly managed by a team of U.S. and Japanese scientists; machine time and experimental results are shared equally between the two nations. Doublet's management structure has distributed control of the project and financial responsibility effectively among the Japanese and American participants.

Several factors, however, may complicate the use of the Doublet approach for more intensive future undertakings. The scope of the project, though extensive by U.S. standards, is quite limited when compared with the scale of potential future projects such as ITER. Only two nations are involved, and the amount of currency transferred is small compared to the projected cost of ITER. Also, the original D III facility was an independent U.S. project, and the Japanese did not become involved until the upgrades were undertaken. Thus, the Doublet project did not have to address facility design and construction issues from the beginning, as a completely collaborative project would.

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[33] The Large Coil Task is described in more detail on p. 159.

[34] For more detailed discussion of Doublet-IIID project, see pp. 162-163.

European Laboratory for Nuclear Research (CERN)[35]

CERN was established in 1954 by several Western European nations. Its objective was to advance knowledge in high energy physics, and it has provided a framework for extensive cooperation in the design and construction of large-scale experimental facilities. It has enabled the European nations to conduct physics research on a scale that would have been impossible for any of them acting independently.

CERN is coordinated by a council consisting of two representatives—one administrative and one technical—from each participating nation. Participants make cash contributions to CERN based on a percentage of each nation's gross national product (GNP). No nation can contribute more than 25 percent of CERN's costs annually. There are no "national rights" within the CERN structure. Participating nations are not guaranteed particular positions for their representatives, specified shares of CERN's procurements, or priority for projects within CERN.

Many features of the CERN management structure could be attractive in future fusion cooperation. For example, the practice of making decisions based on merit, not national rights or privileges, is considered by many analysts to be responsible for CERN's excellent technical record. In addition, involving both technical and administrative people in decisionmaking has resulted in informed, comprehensive decisions.

Yet CERN, like JET, does not provide a complete model for a future ITER. First, CERN relies on cash contributions, which may not be appropriate for ITER. Second, CERN does not have mechanisms in place for protecting sensitive technologies. Third, some more formalized system of "national rights," at least with respect to immediate economic return and longer term research and development return, may be necessary to allocate the benefits of ITER among diverse economies that are not already as interdependent as the individual European Community economies are.

Space Station

The space station, a proposed multi-billion dollar orbiting facility, is the only attempt by the United States to cooperate internationally on a scale financially comparable to future fusion plans. Under U.S. proposals for space station collaboration, the United States would take the lead on the project and invite participation of others, particularly Japan, Canada, and the European Space Agency. Currency exchanges would be minimal. Each of the programs would contribute its own hardware to the station, and these contributions would be joined together at carefully defined interfaces. Each program would retain essential control over development of its own hardware, but the United States would bear overall responsibility for program direction and coordination, for overall systems engineering and integration, and for development and implementation of overall safety requirements. This approach is intended to ensure compatibility and cooperation without transferring technology that the partners may wish to protect.

Some aspects of the space station project could provide a model for large-scale fusion collaboration. In particular, the space station may develop a workable mechanism for limiting the undesirable transfer of technology among the participants. In addition, it is likely that administrative aspects of the agreement might have relevance to future joint undertakings in fusion. Both the space station and a future fusion collaboration such as ITER would have to address issues such as ownership of equipment, intellectual property rights, dispute settlement, liability, selection and assignment of personnel, and establishment and maintenance of safety standards. If the space station can resolve these issues successfully, it could provide a model for ITER.

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[35] This dicussion based on pp. 92-93 of the National Research Council report, *Cooperation and Competition*, op. cit.

In many ways, however, it is difficult to apply the space station approach to future fusion collaborations. The space station is designed to be modular, with participants contributing independently developed components. As noted earlier, the independent development approach would probably be unacceptable and unworkable for ITER. In addition, the United States is taking the lead on the space station, dividing tasks and shouldering much of the cost. It is not clear that such an approach in a major fusion collaboration would be acceptable to either the United States or other participants. Moreover, it is not certain that the United States would accept a subordinate role in a fusion collaboration if another nation were to assume leadership of the project. Fusion projects also have to address siting issues, which the space station avoids because it is not located on national territory. Finally, the space station project does not include the Soviet Union, and thereby avoids the additional security and diplomatic concerns introduced by Soviet participation.

Summary of Potential Management Approaches

It is unlikely that any existing cooperative project will provide a model management structure for a major international effort such as ITER. The strengths and weaknesses of existing projects, with respect to large-scale fusion collaboration, are summarized in table 7-3.

Table 7-3.—Applicability of Existing Projects to Future Fusion Collaboration

Project	Strengths	Weaknesses
INTOR	• Proven approach to project design phase • Most extensive fusion collaboration involving the Soviet Union	• Poorly suited for construction and operation
JET	• Successful design, construction, and operation of world-class facility	• Negotiated within preexisting cooperative framework • Might not address technology transfer issues adequately
LCT	• Successful joint research project • Could provide for control of technology transfer	• United States was lead agency and bore majority of costs • "Independent development" approach might be unworkable for ITER • Might not ensure technical equality of participants, depending on distribution of tasks
D III	• Successful management structure	• United States was lead agency and bore majority of costs • Small-scale project when compared with ITER • Joint project dealt only with upgrade of previously constructed experiment • Involves hard currency transfer
CERN	• Successful design, construction, and operation of world-class high-energy physics program • Not bound by "national rights" system	• Involves hard currency transfer • Might not address technology transfer issues adequately • Lack of "national rights" system may limit equitable allocation of project benefits
Space Station	• Successful conclusion of negotiations will show that large-scale, multi-year, and multi-billion dollar collaborations can be established by the United States	• Negotiations have not been finalized • Independent developments approach might be unworkable for ITER • Does not address siting issues • Provides no experience with Soviet participation

SOURCE: Office of Technology Assessment, 1987

COMPARISON OF INTERNATIONAL FUSION PROGRAMS

Comparing levels of effort among the international fusion programs is complex. Qualitative measures show that the programs are similar in direction and achievement, but these measures are subjective. Quantitative measures are more objective, but they may be distorted. Moreover, different techniques give different results.

Qualitative Comparisons

Qualitative comparisons show that the four major fusion programs are comparable in levels of effort and accomplishment and in their near-term research objectives, although the stated long-term goals and rationales for the programs differ (see table 7-4). Three of the programs operate tokamak experiments of similar capability and complexity, and the fourth (the Soviet Union) is in the process of building a large tokamak of somewhat similar capability; each program also studies alternative confinement concepts. All of the programs recognize the need for a next-generation experiment during the mid-1990s to advance fusion technology and science.

Table 7-4.—Program Goals of the Major Fusion Programs

Program Goal	Rationale
U.S.	
Demonstrate science and technology base for fusion power	Determine potential as an energy option
EC	
Prototype construction	Develop energy option Promote industrial capability Strengthen political unity
Japan	
Demonstration plant	Develop energy option Fulfill national project
U.S.S.R.	
Fusion hybrid system[a]	Support fission program Maintain international activity

[a]Fusion hybrids are discussed in app. A.

SOURCE: Michael Roberts, Director of International Programs, U.S. Department of Energy, Office of Fusion Energy, briefing on "International Discussions on Engineering Test Reactor," before the ETR Workshop, Rockville, MD, July 16, 1986.

Figure 7-1 compares the programs' research and development emphases on confinement concepts, and figure 7-2 compares their technology development efforts.[36] Variations among programs are influenced by differing program concentration, funding levels, technological capabilities, and program history.

Quantitative Comparisons

There are a variety of ways to compare quantitatively the levels of effort among the U.S., EC, and Japanese fusion programs, but each way has flaws. (Data for the Soviet Union is not included in this discussion; it is difficult to obtain reliable information on the size of the Soviet program, its funding level, and the number of people it employs.) Figure 7-3 compares DOE's estimates of the annual fusion budgets of the three programs converted into dollars. According to this figure, the United States has had the highest level of effort in fusion research. However, this conclusion is dependent on the exchange rates used in the currency conversion. The relative magnitude of the U.S. effort is due in part to the extraordinary strength of the dollar in the mid-1980s with respect to European and Japanese currencies. To the extent that goods and services purchased with fusion research funds are not traded on international markets, fluctuations in exchange rates distort the calculations of relative expenditures. Sudden shifts in the value of the dollar have dramatic effects on dollar-based comparisons of the fusion budgets, but do not represent actual changes in fusion work effort.

To correct for distortions from fluctuating exchange rates, DOE has used another method to compare fusion programs.[37] In this method, the

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[36] The discussion in this and the following paragraph is based on documentation by Dr. Stephen O. Dean, President of Fusion Power Associates and author of figures 7-1 and 7-2. His insights represent a view commonly held by the fusion community regarding the relative levels of effort among the major fusion programs. The technical characteristics of the confinement concepts are explained in ch. 4.

[37] John Willis, U.S. Department of Energy, Office of Fusion Energy, Oct. 9, 1986, personal communication to OTA.

Figure 7-1.—Emphases of Major Programs on Confinement Concepts, 1986

BLOCK \ CONFINEMENT CONCEPT	TOKAMAK	TANDEM MIRROR	STABILIZED BUMPY TORUS	STELLARATOR/HELIOTRON/TORSATRON	REVERSED FIELD PINCH	OTHER PINCH	COMPACT TOROIDS	ALTERNATE FUELS/MATERIALS
US	●	▲		■	■	▲	■	▲
JAPAN	●	■	■	●	■		■	
USSR	●	■		■	▲	▲	▲	
EC	●			■	■			

● = MAJOR EFFORT
■ = MODERATE EFFORT
▲ = MINOR EFFORT

SOURCE: Fusion Power Associates.

Figure 7-2.—Emphases of Major Programs on Technology Development, 1986

PROGRAM \ TECHNOLOGY AREA	SUPERCONDUCTING MAGNETS/CRYOGENICS	NEUTRAL BEAMS	RF HEATING	PELLET FUELING	TRITIUM HANDLING	REMOTE MAINTENANCE	FIRST WALL AND ATTACHMENTS	BLANKET	SHIELD	MATERIALS STUDIES	PARTICLE HANDLING	IMPURITY CONTROL	DIAGNOSTICS	COMPUTING, DATA PROCESSING AND CONTROL	ENERGY STORAGE, TRANSFER AND SWITCHING	ADVANCED REACTOR STUDIES	ALTERNATE APPLICATIONS	ENVIRONMENT AND SAFETY	ATOMIC PHYSICS
U.S.	■	▲	●	●	■	▲	■	▲	▲	■	■	■	●	■	▲	▲	▲	■	▲
JAPAN	■	●	●	▲	■	●	●	▲	▲	■	■	■	■	■	■	▲	▲	■	■
USSR	▲	■	■	▲	▲	▲	■	▲	▲	■	■	■	■	■	■	▲	▲	▲	■
EC	■	■	●	●	●	●	●	■	■	■	■	■	●	●	■	▲	▲	■	■

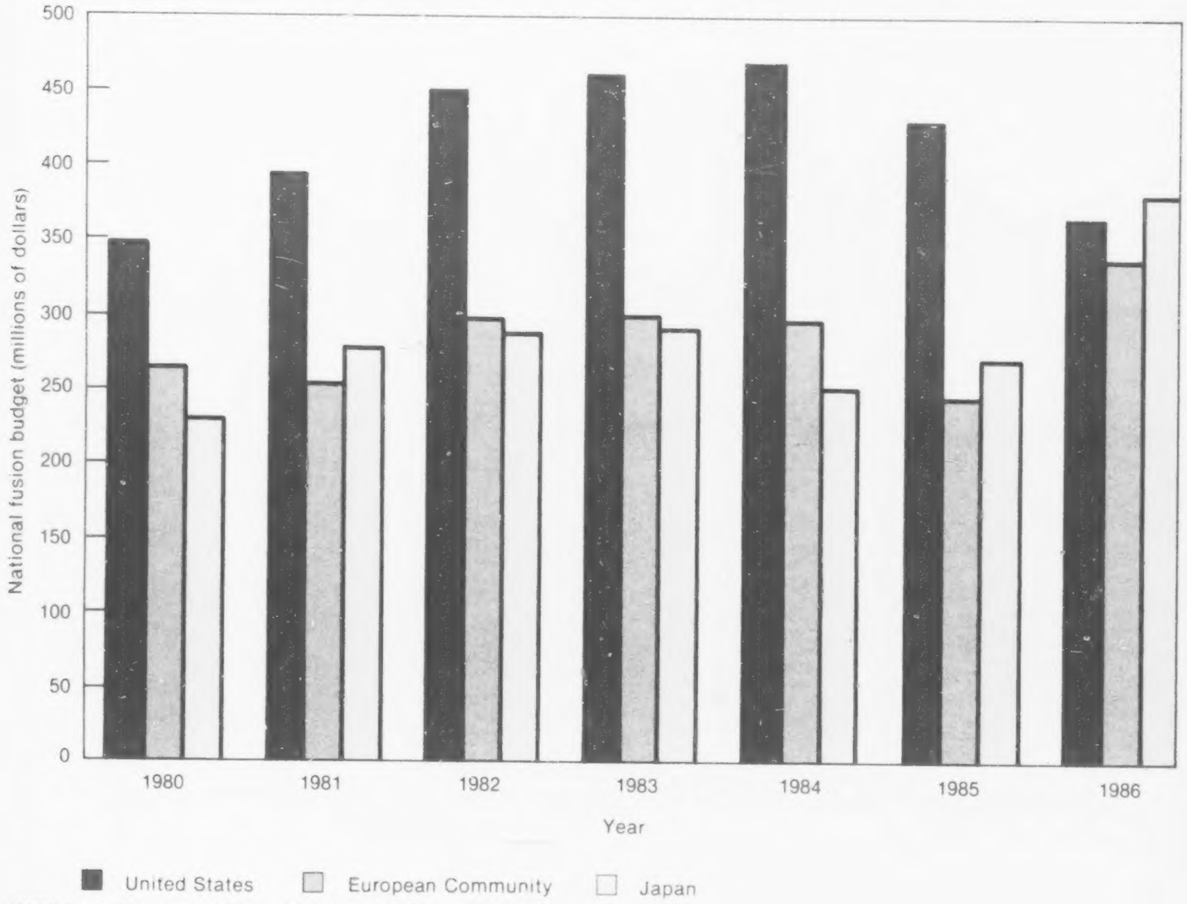
● = MAJOR EFFORT
■ = MODERATE EFFORT
▲ = MINOR EFFORT

SOURCE: Fusion Power Associates

fusion budget of each program is divided by the average annual manufacturing wages prevailing in the country or region, with both values measured in local currency. The resulting value is a measure of the level of effort of each program in units of "equivalent person-years." Comparisons are shown in figure 7-4.

This figure does not literally represent the number of people employed by the respective fusion programs, but rather represents an arbitrary means of comparing relative levels of effort. Expenditures on construction and operation of facilities are converted, along with actual personnel costs, into "person-years" of effort. The validity of this meas-

Figure 7-3.—Comparison of International Fusion Budgets (in current dollars)



SOURCE: U.S. Department of Energy, Office of Fusion Energy, 1986.

ure depends on how well the quoted manufacturing wage rates reflect the wages relevant to the fusion program, on how similar the productivity of labor is between programs, and on how similar the relative values of capital and labor expenditures are among the three programs.

Figure 7-4 shows that by this measure, both the Japanese and the U.S. levels of effort dropped slightly from 1980 to 1986. In both programs, the fusion budget rose in real dollars. However, increases in the average industrial wage rate over the same period resulted in a substantial drop in "equivalent person-years."[38] Unless the majority of the costs incurred by the Japanese and U.S. fusion programs actually rose by the same amount as the wage rate, the conversion to "equivalent person-years" overestimates the decline in these fusion efforts.

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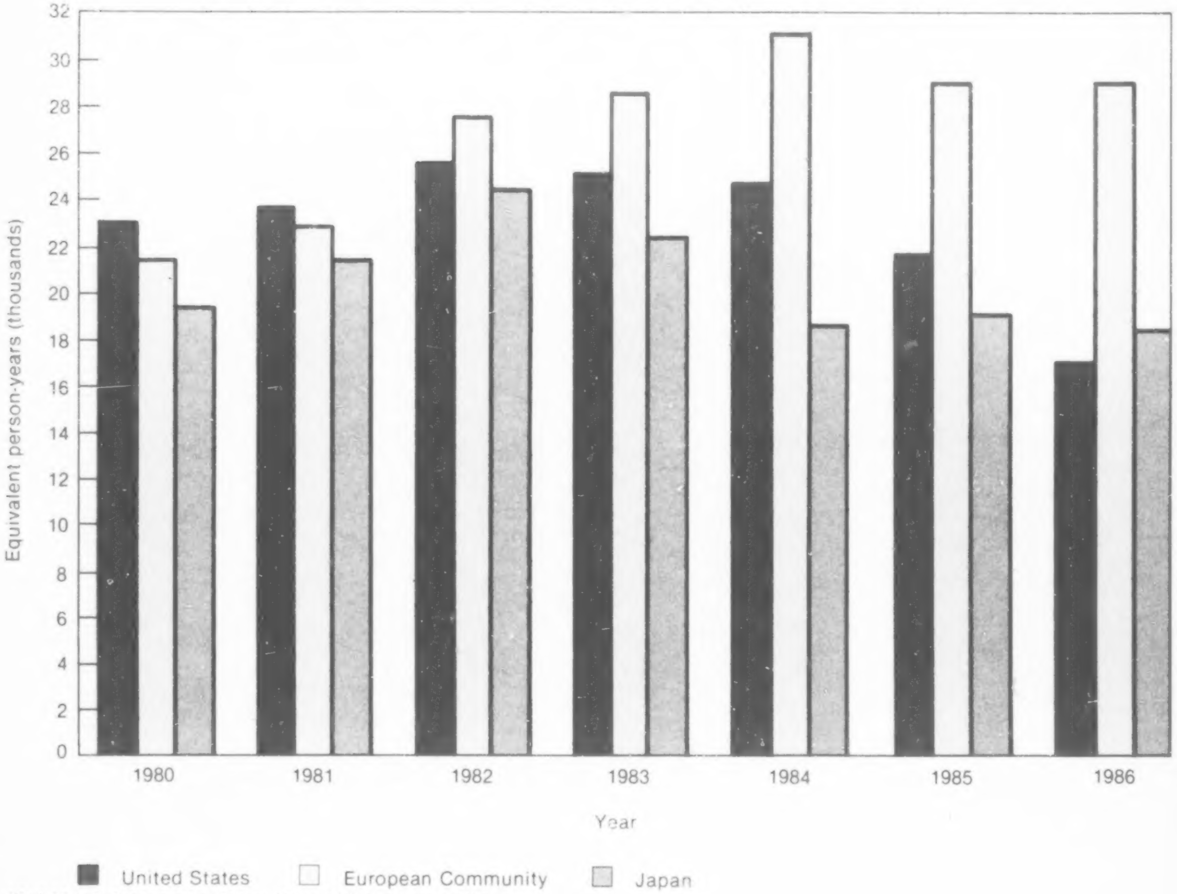
[38] Within the three programs, the average industrial wage rate from 1980 to 1986 rose 38 percent in the United States, rose 76 percent in Japan, and fell 6 percent in the European Community. Over the same period, the fusion budget rose only 4.6 percent in the United States, rose 24 percent in Japan, and rose 97 percent in the European Community, in real dollars.

Figure 7-4.—Comparison of International Equivalent Person-Years



SOURCE: U.S. Department of Energy, Office of Fusion Energy, 1986.

OTA used a third method of comparison to construct figure 7-5, which illustrates the fusion budgets as a percentage of each program's GNP. Under this method, the fusion budgets, as reported by DOE, are divided by the national GNP.[39] Although all values are converted to dollars, inaccuracies in the conversion process should not affect the final result since both GNP values and fusion budgets were adjusted. This approach, which shows that the Japanese devote the greatest proportion of their resources to fusion, measures the relative level of effort of fusion research compared to the rest of the economy of each party. It does not present a comparison of absolute levels of effort, but might be taken to indicate some measure of the commitment of each nation to its fusion program. Of course, many external factors that strongly influence each nation's spending priorities cannot be shown in this figure. For example, this figure does not show the great asymmetry in defense expenditures of the various nations.

An additional problem confounds all of the quantitative methods: the calculations are based on program budgets that are not directly comparable. Budget figures provided by the Japanese

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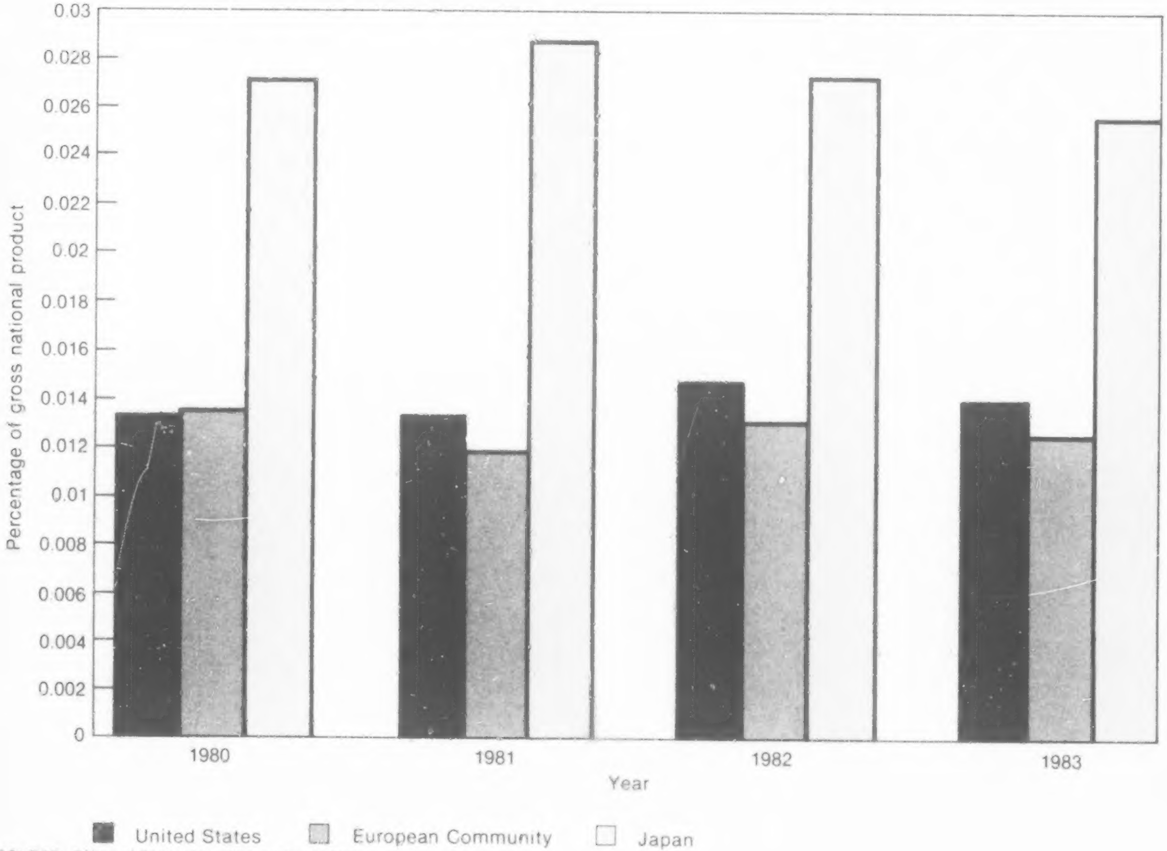
[39] GNP for the European Community was calculated by adding the GNPs of the member nations.

Figure 7-5.—Comparison of International Fusion Budgets by Percentage of Gross National Product



SOURCE: Office of Technology Assessment, 1987.

Government, for example, do not include personnel costs. In the figures shown here, these costs were estimated by DOE for the Japanese program and added to the Japanese figures. In the EC and the United States, distinctions must be made between budget authority (how much the program was authorized to spend) and budget outlay (how much the program actually did spend), and these values can be substantially different.

Obviously, quantitative level-of-effort comparisons based on budget levels may not be reliable. Each method of analysis discussed here suggests different results, and no conclusions can be drawn.

POTENTIAL PARTNERS

Since DOE is investigating the possibility of increased levels of collaboration, an analysis of the goals and incentives of the potential collaborative partners is important.

The United States

Program Goals

The stated goal of the U.S. fusion program is to establish the scientific and technological base necessary to evaluate the potential for fusion energy by early in the 21st century. In 1988, design and construction of the next major facility, the Compact Ignition Tokamak (CIT), may begin, if approved by Congress. The United States recognizes the need to have an engineering test reactor by the mid-1990s to study technical issues related to reactor design and operation, but, due to funding limitations, DOE would like to construct such a reactor in collaboration with one or more other fusion programs. In the conceptual design and supporting R&D proposal currently being negotiated, this project is called the International Thermonuclear Experimental Reactor (ITER). The U.S. fusion program does not currently have plans to construct an engineering test reactor independently. Beyond a collaborative engineering test reactor, the U.S. program has no plans to construct a demonstration reactor.[40]

Views on Collaboration

The United States is extremely interested in future international collaboration, particularly on construction and operation of ITER. A primary incentive is financial; at present, the domestic fusion program is not able to command the financial resources necessary to construct experiments of this scale by itself. Another incentive is DOE's belief that a well-developed scientific and technological base for fusion will be easier to establish if the major fusion programs share information and expertise.

At this point, the U.S. fusion program is considering the possibility of collaborating on ITER with any or all of the major fusion programs. Of the major programs, the United States has cooperated most extensively with Japan. Formal ties between the United States and the European Community are more recent, but the EC fusion program is highly advanced and would be an attractive partner. The U.S. fusion community also highly values input from its Soviet counterpart, which has made significant contributions to past cooperative projects and which continues to make technological advances. However, the politics of the U.S.-Soviet relationship are more volatile than those between the United States and Japan or the EC. This difference will make major collaboration with the Soviet Union the most difficult to arrange.

Nevertheless, Soviet participation in a multilateral fusion project has been supported at the highest levels of both governments. At the Geneva Summit of 1985, President Reagan and General Secretary Gorbachev "advocated the widest practicable development of international collaboration" in fusion research.[41] The United States explicitly made this arrangement conditional upon allied participation, and a strictly bilateral collaboration between the two countries on ITER would be very unlikely.

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[40] See the section of ch. 4 titled "Research Progress and Future Directions" for a more detailed discussion of the U.S. research plans and facility needs.

[41] From statement at the Reagan-Gorbachev Summit, November 1985.

The European Community[42]

Program Goals

The member countries of the European Community are making a long-term investment in fusion for its possible value as a major new energy source that could contribute to Western Europe's future energy security. Collaboration within the EC has been extremely successful; it has been a source of pride.

The Joint European Torus (JET) is the EC's most important experimental fusion facility and the world's largest tokamak.[43] Planning has begun for a second facility—the Next European Torus (NET)—which, like ITER, is intended to confirm the scientific feasibility of fusion and address the question of engineering feasibility. The current schedule for NET calls for a detailed design decision in 1989 or 1990 and a decision on construction in 1993. A third facility envisioned by the EC is a prototype fusion power reactor to demonstrate the economic feasibility of fusion. The timetable for this prototype depends on the success of JET and NET. Construction is projected to begin between 2010 and 2020.

Views on Collaboration

The European Community is interested in international collaboration for a variety of reasons. In recent years, the EC has confronted tight budgets and competing demands for funding, which increase the attractiveness of working with partners outside of Europe. Like other nations, the EC recognizes the substantial benefits of cost savings and knowledge and risk sharing. Moreover, through the JET project, the EC has had positive first-hand experience with the scientific, technical, and management aspects of collaboration. In addition, the EC fusion effort has cooperative relationships with the other programs, principally the United States for which it has considerable respect. It also respects the Soviet and Japanese fusion programs, but contact with them has been less frequent.

Even without international collaboration, the European Community's program has established political support and momentum through JET. The EC has a clear strategy for future fusion research, in which NET plays a vital role, and it appears committed to carrying this program out. Nevertheless, the European Community is willing to investigate prospects for a large-scale collaboration with the other major fusion programs. At the same time, **the EC plans to continue working independently on NET unless and until the ITER effort offers convincing guarantees of success.** The EC might not wish to participate in a major project that is not located in Europe.

The Soviet Union[44]

Program Goals

The Soviet Union has an active fusion research program, which is supported by a strong commitment to nuclear power for geographical and fuel cycle reasons.[45] The breeder reactor is the primary focus of the Soviet atomic energy program for the 1990s, and the fusion reactor is the focus of the next century. The Soviet Union is also investigating the potential of fission-fusion hybrid reactors for its thermal and breeder reactor program.[46]

The Soviet Union is currently constructing a major tokamak experiment, T-15, which is similar in objective and capability to the large tokamaks currently being operated in the United States, EC, and Japan. Completion of T-15 was originally scheduled for 1982, but the project has been delayed repeatedly due to engineering problems and is now expected to operate in 1988. The Soviets are considering construction of a device called the Operational Test Reactor (OTR) to succeed T-15.[47] This device is believed to be analogous to the next-generation devices planned in other major national programs, except that it is also intended to verify how effectively fusion can be used to breed fuel for fission reactors.

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[42] This discussion is based in part on information provided by an OTA contractor, Professor Wilfrid Kohl, in a report titled "The Political Aspects of Fusion Research in Europe." Kohl is director of the International Energy Program at the Johns Hopkins University School of Advanced International Studies.

[43] The JET project is described in detail in "Multilateral Activities."

[44] Information on the Soviet Union's fusion program was provided to OTA by Dr. Paul Josephson, "The History and Politics of Energy Technology: Controlled Thermonuclear Synthesis Research in the USSR." Josephson has studied Soviet science and technology policy issues at the Massachusetts Institute of Technology's Program in Science, Technology, and Society.

[45] Seventy percent of Soviet energy consumption and population is located in the European part of the country, but 90 percent of the fuel resources are located in Siberia and Soviet Central Asia. The cost of transponing the energy thousands of miles from east to west, either in its primary form or as electricity, is high. Therefore, the government is pursuing the rapid commercialization of nuclear energy near the western population centers.

[46] Fission-fusion hybrid reactors use the neutrons generated in fusion reactions to produce fissionable fuel. For more information, see app. A.

Views on Collaboration

The Soviet Union has regularly made proposals to enhance international cooperation in fusion. The INTOR project was initially proposed by the Soviets, as was the genesis of the current proposal for an international next-generation experiment. The Soviet Union has made major contributions to past international projects and has clearly found the activities rewarding.

It appears that budgetary constraints are putting pressure on the Soviet fusion program. While it is difficult to provide actual data on the size of the Soviet fusion budget, a review of Soviet journals indicates that plasma physicists currently are more circumspect in their predictions for fusion power than they used to be, and that they are fighting to retain their fusion budgets in the face of intense pressure from other energy research programs such as breeder reactors.[48]

There is high-level political support for collaboration in fusion, and General Secretary Gorbachev has stressed repeatedly its importance. He raised the issue with President Reagan at the Geneva Summit in 1985 and again in a speech before the Supreme Soviet in 1986. On the latter occasion, he said:

> On the initiative of the U.S.S.R., work involving scientists from different countries has begun on the tokamak thermonuclear reactor project [INTOR], which opens up an opportunity to radically resolve the energy problem. According to scientists, it is possible to create as early as within this century a terrestrial sun . . . thermonuclear energy. We note with satisfaction that it was agreed in Geneva to carry on with that important work.[49]

In addition to incentives to collaborate, there are also obstacles from the Soviet perspective. These include pressures within the U.S.S.R. to avoid technological reliance on the West and shortages of hard currency with which to participate. Another obstacle is any unforeseen deterioration of the U.S.-U.S.S.R. relationship due to political developments unrelated to fusion; in 1980, for example, the Soviet invasion of Afghanistan interrupted cooperative fusion work that had been relatively stable until then.

It appears that the Soviets would be comfortable collaborating with any of the major fusion programs on ITER, judging from the positive Soviet evaluation of INTOR. However, as yet neither the Japanese nor the Europeans have sought to build a machine with the Soviets.[50] **Because of the Soviet Union's relatively long-term involvement with the United States in bilateral scientific agreements, the role of these scientific exchanges in the pursuit of improving relations, the present international outlook of Soviet leaders toward technology, and Soviet respect for American science and technology, the Soviets appear interested and willing to collaborate with the United States.**

Japan[51]

Program Goals

Many Japanese see fusion as the ultimate solution to Japan's energy problems. Japan is more dependent on imported energy than any other major economic power, and the Japanese are concerned about how precarious this dependence makes their economy. Nuclear energy has helped the Japanese decrease their dependence on oil, and Japanese policymakers favor the continued use and development of nuclear power. Japan's general long-range energy policy calls for an increased reliance on conventional nuclear energy over the next 25 years. It is anticipated that this policy will be followed by a reliance on fast breeder reactors around 2010 and a transition to fusion energy about 30 years later.

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[47] Michael Roberts, U.S. Department of Energy, Office of Fusion Energy, briefing on "International Discussions on ETR," Rockville, MD, July 16, 1986.

[48] P. Josephson, "History and Politics," op. cit., pp. 16-19.

[49] M.S. Gorbachev, as cited in Kadomtsev, "Tokamak," *Soviet Life*, August 1986, p. 13.

[50] Mark Crawford, "Researchers' Dreams Turn to Paper in U.S.-USSR Fusion Plan," *Science*, vol. 234, Nov. 7, 1986, p. 667.

[51] This section is based in part on a report completed for OTA by Dr. Leonard Lynn, "Political Aspects of Fusion Research in Japan." Lynn is a professor who analyzes Japanese science and technology policy in the Department of Social and Decision Sciences at Carnegie-Mellon University.

The largest experimental fusion facility in Japan is JT-60. Japanese scientists have begun conceptual design studies for a next-generation tokamak, the Fusion Experimental Reactor (FER), which is intended to succeed JT-60. FER, which could be built in the late 1990s, would resemble NET or ITER and probably would be designed to achieve ignition and demonstrate the technical feasibility of the nuclear fusion reactor.

Views on Collaboration

International collaboration is attractive to the Japanese for many of the same reasons that it is attractive to other countries. The Japanese, like others, feel that the financial and human resources required to construct a next-generation fusion device may be too great a burden to bear alone. Moreover, the Japanese have both contributed and received valuable technical information from past fusion cooperative projects.

Although the Japanese are interested in collaborating on fusion research, there may be some obstacles to such collaboration. The Japanese confront a major debt burden that has grown rapidly in the last few years and that has increased government pressure to cut spending.[52] In addition, the Japanese might be unwilling to participate if the experiment is not sited in Japan.

The Japanese are willing to explore the possibility of multilateral collaboration on ITER, however, and they are currently participating in discussions of the project with the United States, the European Community, and the Soviet Union. **Of the three, Japan appears most interested in collaborating with the United States.** In addition to extensive cooperative experience with the United States, the Japanese also have a bilateral arrangement with the EC that involves meetings of experts and information exchange.[53] However, the Japanese and European programs currently are less familiar with each other than either is with the United States. The Japanese have the least experience cooperating with the Soviet Union.

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[52] Ibid., pp. 46-47. Public debt climbed from 22 trillion yen in 1976 (13 percent of GNP) to 130 trillion yen in 1985 (42 percent of GNP). In 1986, the cost of servicing this debt accounted for more than 20 percent of government expenditures. This compares to 14 percent of government expenditures going to service the U.S. national debt in 1985.

[53] Ibid., pp. 42-43.

PROSPECTS FOR INTERNATIONAL COOPERATION

U.S. Plans for Future Cooperation

DOE is interested in the prospects for more extensive international cooperation on future magnetic fusion experiments. In fact, a recent DOE report on international activities in magnetic fusion states:

> The objectives of U.S. international collaboration are to share the many high priority tasks, to reduce the total costs associated with the required major facilities and to combine intellectual forces in pursuit of the most essential problems.[54]

International collaboration in fusion research and development has become a key factor in DOE's program planning.

Possible Areas for International Cooperation

There are several possible areas of cooperation delineated in DOE's report.[55] These areas are linked to the four key technical issues in the DOE Magnetic Fusion Program Plan (see the section in ch. 4 titled "Key Technical Issues and Facilities" under "Research Progress and Future Direc-

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[54] U.S. Department of Energy, Office of Fusion Energy, *International Program Activities in Magnetic Fusion Energy*, op. cit., p. 1

[55] Ibid., Attachment 3, pp. 1-5.

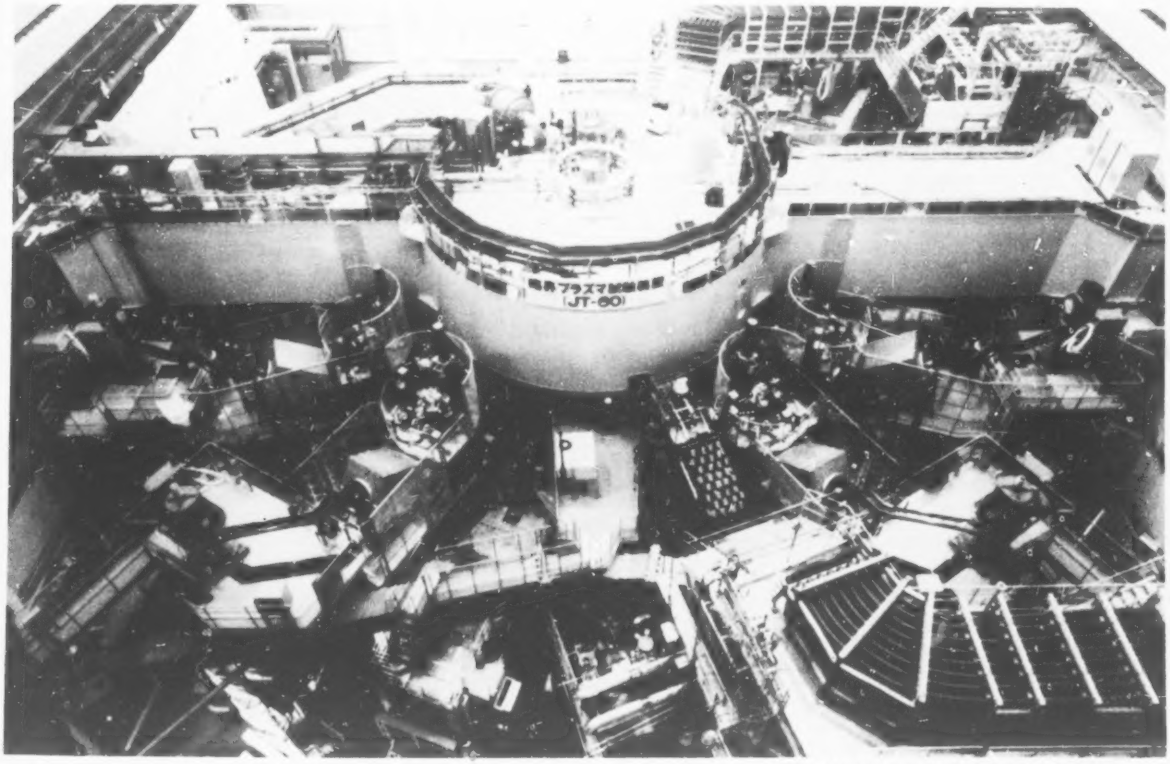

Photo credit: Japan Atomic Energy Research Institute

The JT-60 tokamak, located in Naka-Machi, Japan.

tions"). In confinement systems, DOE states that possible initiatives include gaining long-term access to the JET experimental programs and possibly those at JT-60, developing a coordinated program to develop the reversed-field pinch concept, and using selected foreign facilities to continue development of superconducting magnets. In burning plasmas, the United States would seek foreign participation in the planning and operation of CIT. In nuclear technology for fusion systems, DOE is investigating proposals to extend the current cooperative activity in technology research and development and to coordinate efforts in development of tritium handling technology. In fusion materials, DOE further proposes to coordinate research with the other major programs.

Considerations of the International Thermonuclear Experimental Reactor

To date, DOE's proposal to design ITER collaboratively has drawn the most attention among the many cooperative efforts outlined in DOE's report. Within the framework of the Versailles and Geneva summits, DOE has been involved in negotiations with the other major fusion programs to develop the conceptual design and supporting R&D for ITER. The proposal does not currently extend to joint construction and operation of the experimental facility. At the conclusion of the conceptual design effort, the parties would be free to build such a device, either alone or collectively.

The Versailles Economic Summit.—Several nations participate each year in an economic summit meeting.[56] These nations began considering the implications of technology for economic growth and employment at the urging of French President Mitterand in 1982 when the meeting was held in Versailles, France, and a process for considering specific ideas on this topic was established. The prospect of international cooperation in magnetic fusion was one of 18 ideas specifically investigated. Cooperative efforts in fusion research have been discussed since then, and a great deal of effort has gone into developing plans for a workable joint undertaking.[57]

Under the framework established at the Versailles summit, the Fusion Working Group was created in 1983. The Fusion Working Group is involved in early joint planning efforts and discussions aimed at identifying necessary major facilities. In 1985, the Fusion Working Group created the Technical Working Party to consider technical and research-related issues in international fusion projects. In late 1985, the Technical Working Party endorsed the U.S. plan to construct CIT.

In 1986, the Fusion Working Group reached a consensus on the desirability of future collaborative activities. Participants issued a joint statement that an engineering test reactor (now called ITER) is a common midterm goal for the fusion programs of the United States, Japan, and the European Community.[58]

The Geneva Summit.—Fusion cooperation was also discussed by the United States and the Soviet Union at the Geneva summit in November 1985. Prior to the summit, in an October 1985 meeting between French President Mitterand and Soviet General Secretary Gorbachev, Gorbachev had expressed interest in pursuing international collaboration on a large next-generation fusion experiment. The Geneva summit between President Reagan and Gorbachev, held in Geneva, Switzerland, followed up on this point. At the conclusion of the meeting, President Reagan and General Secretary Gorbachev issued a joint statement supporting fusion collaboration to the "widest degree practicable." The statement did not recommend a specific proposal or approach.

Current Status of the ITER Project.—No formal agreement has been reached on the ITER project. Recently, the United States proposed that the potential partners begin a 3-year joint planning activity to do conceptual design and supporting R&D for the device. Areas of collaboration would include defining the scope of the project, developing a conceptual design for the device, and coordinating the research needed to support the design effort.

Representatives from the United States, Japan, the European Community, and the Soviet Union met in March 1987, in Vienna, Austria, to discuss the conceptual design phase of such a project. This meeting, held under IAEA auspices, marked the first time that all four parties met to discuss collaboration on ITER. The meeting produced general agreement on the nature of the project and the necessary steps to formalize it. The IAEA stated at the end of the meeting:

> The Parties were favorably disposed to the proposal for joint conduct of conceptual design and supporting R&D for an international thermonuclear experimental reactor. The Parties reached an understanding that the proposal was a sound basis for further discussion. The four Parties will each identify their representative to a group of experts to make proposals for a common set of detailed technical objectives for the conceptual design and to prepare the basis for further consideration by the Parties.[59]

In some ways, the arrangement proposed by the United States resembles the International Tokamak Reactor (INTOR) study. The proposal is more extensive, however, than INTOR. First, ITER deliverables would have a defined schedule, whereas the INTOR schedule is indefinite. Second, the ITER project would receive higher level attention than INTOR. Third, under the ITER project, there would be full-time design teams working in each program; the INTOR design teams are part-time. Finally, the ITER project, unlike INTOR, would include cooperation on supporting R&D.

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[56] Participants are the United States, Canada, the Federal Republic of Germany, France, Italy, Japan, and the United Kingdom. The European Community as a whole is also represented.

[57] Michael Roberts, Director of International Programs, U.S. Department of Energy, Office of Fusion Energy, briefing on "International Programs in Fusion," presented to ERAB Fusion Panel, Washington, DC, May 29, 1986.

[58] Summit Working Group on Controlled Thermonuclear Fusion, *Summary Conclusions*, Schloss Ringberg, Jan. 17, 1986.

[59] International Atomic Energy Agency, as quoted in *Executive Newsletter*, Fusion Power Associates, April 1987, p. 4.

DOE has proposed that there be a full-time group of managing directors to coordinate the planning effort. According to DOE, this phase of the activity could utilize the International Atomic Energy Agency as an umbrella organization to facilitate the project. For simplicity, the coordinating site could be located at the IAEA headquarters in Vienna, Austria. No other site agreements would be necessary at this stage because all other work would be undertaken within the national programs.

The total cost of the 3-year conceptual design phase of ITER is estimated to be between $150 million and $200 million, which includes its supporting R&D. The U.S. cost of the undertaking is projected at between $15 million and $20 million annually. This annual budget represents about a tripling of the amount the United States currently spends on design studies.

DOE anticipates that the conceptual design phase of the ITER project will occur between 1988 and 1990. At the completion of this phase, interested parties would be in a position to begin negotiations on whether or not to jointly construct and operate the device. Any party could withdraw at this point, decide to construct and operate the experiment independently, or choose to pursue the effort collaboratively.

Analysis of U.S. Proposal for ITER

The U.S. Government's recent proposal marks the first step toward a collaborative ITER. No agreement has been reached; the details of the proposal will be modified during negotiations with other fusion programs. Therefore, it is impossible to assess the proposal completely.

The proposal is based on the INTOR model, which provides an example of successful, if limited, cooperation on project design. Like INTOR, in which the Soviet Union participates without threatening U.S. national security, this proposal does not raise technology transfer concerns because it will include only common design, not common technology development.

The current proposal does not address the problems that would be encountered in jointly constructing and operating ITER. These obstacles will still arise when and if the decision is made to build and operate the device. The current proposal does provide a mechanism whereby the conceptual design and supporting R&D can be completed, enabling informed decisions about proceeding with collaboration to be made at a later date.

Completing the conceptual design phase of ITER may help resolve some of the obstacles to subsequent collaboration. For example, the conceptual designs developed over the next 3 years may enable concerns about technology transfer to be analyzed specifically and their implications for national security to be resolved definitively. Furthermore, issues such as siting the facility or determining a technically acceptable project design may be settled, either through the initial phase of the project or through concurrent discussions and negotiations. **At the completion of the design phase, the major fusion programs should be better situated to develop detailed plans for further collaboration.**

The current ITER proposal begins conservatively, utilizing an already well-established cooperative arrangement. Participants will be able to work on the project without making a firm commitment to future involvement in joint construction and operation. Perhaps most importantly, U.S. Government agencies will have more time and additional information with which to establish clear policy guidelines.

SUMMARY AND CONCLUSIONS

Magnetic fusion has a long history of international cooperation. For the future, the major fusion programs recognize the benefits of sharing costs, risk, and knowledge; they value the opportunity to achieve collectively what no program could afford to achieve alone. Any or all of the major world fusion programs would be technically attractive collaborative partners for the United States. Higher levels of cooperation have drawbacks, however. Cooperation may actually increase the total cost and risk associated with fusion projects, and the benefits of knowledge sharing may be cut short if technology threatening national security or national competitiveness is transferred to the partners.

There are many successful examples of cooperation in fusion research and other scientific areas. JET, for example, is a collaborative undertaking in which the major European fusion programs have jointly constructed and operated a world-class tokamak facility. CERN, a major nonfusion project, is an example of the European nations pooling their resources and developing a state-of-the-art high-energy physics program.

While future cooperation can build on the solid foundation of the past, collaborative projects such as ITER will have to resolve many new issues. Collaboration on this scale involving countries outside Europe is unprecedented. Negotiating and approving the necessary international agreements will be possible only if the parties involved are committed both to the collaborative project and to their domestic programs. International collaboration cannot substitute for a domestic fusion program. If the domestic program is sacrificed to support an international project, the rationale for collaboration will be lost and the ability to conduct the project successfully will be compromised.

The U.S. Government's current ITER proposal appears to be a workable first step toward a major experimental facility. The proposal minimizes the risks in the project's early stages by decoupling design from construction and operation.

The proposal has far to go. Although successful completion of the conceptual design and supporting R&D will be important for addressing the issues related to construction and operation, the design process alone will not resolve these issues. In the United States, at the moment, the most significant issue on joint construction and operation is the possible transfer of militarily relevant technology. Agencies within the U.S. Government disagree about the severity of this problem, and the dispute must be settled internally before a major collaboration can proceed.

Project location is another critical issue. Just as siting was a major problem for JET, it is likely that a decision on ITER location will not come easily. What does seem clear is that it is unlikely that either the United States or the Soviet Union will be chosen as the site for ITER.

Ultimately, reaching an agreement to jointly construct and operate an international experiment will require high-level government support. A clear presidential decision to support the undertaking will be required. Even that, by itself, is insufficient to guarantee the viability of a project involving all branches of the U.S. Government and extending over several Presidential Administrations. Moreover, the national programs will have to formalize their support in an agreement that will establish confidence in the management and operation of the project.

DOE considers international collaboration on ITER and other projects essential to the progress of the U.S. fusion program. If more extensive cooperation proves impossible or unacceptable, DOE's program plans must be reevaluated: either the U.S. program will need more funding or its schedule will have to be slowed down and revised.

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Future Paths for the Magnetic Fusion Program

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Chapter 8

Future Paths for the Magnetic Fusion Program

The likelihood that fusion will be developed as a future energy supply option is affected—although not completely determined—by policy choices made today. A decision to accelerate fusion research does not ensure that fusion's potential will be successfully realized, any more than a decision to terminate the current research program implies that fusion will never be developed. Nevertheless, near-term decisions clearly influence the pace of fusion's development. The sooner we wish to evaluate fusion as an energy supply technology, the more important our near-term decisions become. Over the next several decades, the fusion research program can evolve along any of four largely distinct paths:

1. With substantial funding increases, the U.S. fusion program can complete its currently mapped-out research plan independently. This plan is intended to permit decisions concerning fusion's commercialization to be made early in the next century. This approach is called the *"Independent"* path.
2. At only moderate increases in U.S. funding levels, the same results might be attainable—although possibly somewhat delayed—if the United States can work with some or all of the world's other major fusion programs (Western Europe, Japan, and the Soviet Union) at an unprecedented level of collaboration. This path is termed *"Collaborative."*
3. In the absence of major collaboration, a flat or declining funding profile would force significant changes to be made in the program's overall goals, including a recognition that fusion's commercialization would be delayed from current projections. This path is called *"Limited,"* indicating that progress in some critical areas would be impossible without additional resources.
4. Shutting down the fusion program would foreclose the possibility of developing fusion as an energy supply option unless and until research were resumed. On this *"Mothballed"* path, progress towards fusion in the United States would halt. Work would probably continue abroad, although possibly at a reduced pace; resumption of research in the United States would be possible but difficult.

Current Department of Energy long-range plans for the fusion program are aimed at the "Collaborative" path. If recent funding declines continue, however, or if the United States does not successfully arrange its participation in major collaborative activities, the U.S. fusion program will evolve along the "Limited" path.

KEY ISSUES AFFECTING THE EVOLUTION OF FUSION RESEARCH

The four paths are differentiated by the degree of commitment and the level of funding provided by the U.S. Government for fusion research. Path characteristics and the choices between them are determined by several factors, including: 1) the likelihood of technical and commercial success in developing fusion technology; 2) the perceived urgency with which a new supply of electricity is needed; 3) the advantages and risks of large-scale international collaboration; 4) the implications of requirements for expensive research facilities; and 5) the value of the "auxiliary benefits" associated with fusion research such as scientific understanding, education, and technological development. Another factor, the potential for surprise inherent in any new technology, may also be an important aspect of one's choice of research approach; however, such a factor is not amenable to analysis.

Discussions earlier in this report have addressed many of these factors, which are summarized below:

- **Likelihood of Success**: In evaluating the likelihood of program success, technical success must be differentiated from commercial success. According to chapter 4, the risk of *technical failure* appears small, particularly if operation of the Compact Ignition Tokamak (CIT) does not uncover serious problems.[1] If CIT operates as anticipated, it seems likely that a fusion device capable of producing electricity can be developed.

  However, the risk of *commercial failure*—the development of a technology that does not interest potential users—is much harder to evaluate. The commercial attractiveness of fusion energy will depend not only on its cost, but also on conditions unrelated to fusion technology that cannot be estimated at present. Different opinions as to the likelihood of successful commercialization and the attractiveness of fusion over other electricity alternatives affect the priority given to fusion research.
- **Perceived Urgency**: Chapter 5 concluded that estimates of future electricity demand neither require nor eliminate fusion as a possible energy source. It appears that electricity technologies other than fusion—principally coal and nuclear fission—should be capable of supplying ample power at reasonable prices through at least the middle of the next century. However, uncertainties as to the continued acceptability of fossil fuels and nuclear fission provide incentives to explore the potential of improved energy efficiency and to develop alternative energy sources. Different estimates of the future attractiveness of coal and nuclear fission, and different judgments of the ability of various alternatives to replace coal and/or fission, affect one's perception of the urgency of fusion research and development.

  None of the research paths presented in this chapter call for a crash program to develop fusion. It is very difficult to formulate a credible scenario of major, irreversible electricity shortages in the early 21st century that would require fusion's development on a schedule faster than that discussed in chapter 4.
- **Advantages and Risks of Large-Scale International Collaboration**: It appears possible that large-scale international collaboration could enable the United States to make progress towards assessing fusion's potential at a substantially lower cost than would be required for the United States to proceed independently. Chapter 7 discussed the advantages and risks of large-scale international collaboration in future fusion projects. Different evaluations of the costs and benefits of large-scale collaboration, which were presented in chapter 7, affect one's willingness to consider undertaking the next stages of fusion research collaboratively. In addition, different assessments of the obstacles to international collaboration may affect one's willingness to negotiate a collaborative agreement.
- **Implications of the Need for Expensive Research Facilities**: Chapter 4 identified several major research facilities that may be required to evaluate fusion's potential. The total worldwide cost of these facilities has been estimated at $6 billion, with a next-generation engineering test reactor alone expected to cost well over $1 billion. **As long as multibillion-dollar facilities are necessary to assess fusion's potential, development of fusion power cannot proceed without strong financial support at the highest levels of government.** The private sector will not be willing to finance fusion research until fusion's potential is clearer.

  The need for major facilities, along with the need to conduct a diverse array of supporting research, means that the fusion research program will not make progress towards evaluating fusion's energy potential if its funding is too low. With insufficient funding, the program must either delay complete evaluation of fusion's potential or await technological developments (which may never be realized) that lower the cost of the research remaining to be done.

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[1] CIT is described in the section of ch. 4 titled "Key Technical Issues and Facilities."

- **Near-Term Benefits**: Chapter 6 discussed near-term benefits of fusion research such as increasing scientific understanding, educating and training skilled technical personnel, and developing technologies with economic and defense applications. Different values assigned to these benefits, and different estimates of the benefits that would have been derived had the resources spent on fusion been allocated elsewhere, lead to different levels of emphasis on fusion research.
- **Potential for Surprise**: In many respects, fusion technology will be unlike any existing technology, and it may open up capabilities and applications that cannot be foreseen today. Like other qualitatively new technologies, fusion's most significant impacts may be totally different than those that were expected prior to its introduction. Some observers might oppose fusion's development because of this inherent potential for unanticipated consequences; others would eagerly support exploration of the technology primarily because of the new possibilities it may offer. Since unforeseen capabilities or consequences are by definition impossible to predict, this report cannot and does not address them.

The possible advantages and disadvantages of each of the four paths outlined at the beginning of this chapter are described below, along with the assumptions that would lead to each's selection. The discussions of the paths are interdependent; in many cases, the advantages of selecting one approach also describe the disadvantages of selecting another. The paths are discussed in general terms, and the detailed structure of the fusion research program is not specified under any of them. Extensive additional study would be required to determine the best way to implement each path.

THE INDEPENDENT PATH

Description

The goal of the Independent path would be to aggressively establish the scientific and technological base necessary to evaluate fusion's potential and to decide by the early 21st century whether to proceed with a demonstration reactor. All the facilities required to establish this base would be funded and operated domestically under this approach. The exact funding necessary for this path cannot be determined without detailed additional examination, but considerably more support would be required than is currently available to the fusion program. On average, between $500 million and $1 billion per year probably would be required over the next 20 years, with peak annual funding possibly exceeding $1 billion. Widespread international cooperation might continue, but it would fall well short of the shared decisionmaking and funding that would characterize the Collaborative approach. The Independent path is similar to the one specified (but not funded) in the 1980 Magnetic Fusion Energy Engineering Act.[2]

Motivations and Assumptions

Choice of this path would be motivated by the assumption that evaluating fusion's potential early in the next century is an important national goal. The probability of success and the need for developing fusion would both be assumed high enough to justify considerably increasing the current U.S. investment in fusion research.

The benefits of conducting fusion research without depending on the participation of other countries would be assumed to outweigh the cost savings and other possible advantages of large-scale international collaboration. Although the near-term domestic benefits of fusion research probably also would be highly valued, the prospects of developing a viable energy technology would be the primary motivation for selecting this path.

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[2] This act is described in the section of ch. 3 titled "The 1980s: Leveling Off."

Advantages

Control Over Research and Development.—Under this approach, the United States would be fully self-sufficient in acquiring the information needed to assess fusion's potential. Decisions made in other countries or difficulties in large-scale international collaboration would not affect the U.S. ability to evaluate fusion's potential on a time scale of its own choosing. Under this approach, the United States could attempt to regain a position of world leadership in fusion research, rather than accept the technological parity required for true collaboration and interdependence.

If the United States were to go on to make a positive assessment of fusion's potential, and if the U.S. technological capability in the field were unmatched by other international fusion programs, the United States would have the advantage of leading the development and commercialization of fusion technology.

Energy Supply.—If the United States were to make a positive evaluation of fusion's potential as a result of pursuing this approach and were then able to develop and commercialize fusion technology, a new, potentially attractive source of energy would become available. Even if fusion were not viewed as preferable to other energy technologies, investment in the technology might still be justified since fusion would be available as a hedge against unforeseen or underestimated difficulties with other energy sources.

Manpower, Infrastructure, and Technology Development.—Conducting fusion research independently could have significant domestic benefits, in terms of training personnel, acquiring a domestic fusion infrastructure, and developing associated technologies. Since more funds devoted to the fusion effort would be spent domestically than under any of the other research approaches, these domestic benefits would be realized to a greater extent under this approach. Moreover, the United States would not be dependent on externally acquired information or technical expertise.

International Stature.—Through this research approach, the United States would be able to demonstrate its technological capability and bolster its international stature. In addition to the potential economic returns, being in a position of world leadership could give the United States significant leverage in future cooperative projects and could make the United States a more desirable cooperative partner.

Disadvantages

Cost.—The principal disadvantage of this research approach is its cost, which is considerably higher than that of any other approach. Fusion is not guaranteed to succeed, and the investment in fusion research may not "pay off" with an attractive energy technology. In this case, the investment in fusion research might be considered wasted. Benefits of the fusion program such as scientific return, training of personnel, technological development, and international stature—hard as they are to measure—are unlikely to justify the full cost of independently developing fusion technology.

Potential Overemphasis.—A sense of urgency and direction is necessary in order for the fusion program to command the resources it would require under the Independent path. However, the risks of program failure are increased if an exaggerated sense of urgency pushes the research effort faster than it can responsibly proceed and prematurely forces key decisions. A balance must be struck between proceeding with determination and direction, which is necessary, and rushing into a "crash program," which can be counterproductive.

A more subtle risk could arise if fusion were emphasized at the expense of improving the existing sources of energy supply, increasing the efficiency of energy use, or developing other energy supply alternatives. If U.S. long-term energy research concentrates heavily on fusion, the implications of technical or commercial failure could be serious. Therefore, if concern over energy supply motivates more intense fusion research, it should also motivate energy research in nonfusion areas.

THE COLLABORATIVE PATH

Description

Ideally, the Collaborative path would accomplish the same technical tasks as the Independent path on a similar time scale. However, the Collaborative path would use the combined resources of the world's major fusion programs, making it possible for the individual contribution of any one program to be smaller than would be needed to perform the same tasks alone.

With large-scale international collaboration, the U.S. fusion program would require only modest increases in funding above current levels to evaluate fusion's feasibility early in the 21st century. Annual funding on the order of $400 million to $500 million probably would be necessary over the next 20 years, with the total being highly dependent on the degree of cost-sharing attainable through collaboration.

Motivations and Assumptions

Choice of this approach, like the Independent approach, is based on the assumption that evaluating fusion's potential in the early 21st century is an important national goal. The assumed probability of success and the perceived need for fusion power would be high, as they would be under the Independent path. The major difference between this path and the Independent path is that under this approach the benefits of large-scale international collaboration would be assumed to outweigh the disadvantages. The United States would consider self-determination in fusion either impossible or not worth the price.

Activities under the Collaborative path could take the form of joint construction and operation of major facilities, in which several nations' fusion programs would be simultaneously involved. Activities could also take the form of allocating various research tasks to particular programs. If such an allocation were done, all programs would eventually need to obtain data (which is rather easily shared) and expertise or "know-how" (which is harder to transfer) from the program that had done a particular piece of research.

The near-term benefits of fusion research would not be judged important enough under this approach to justify conducting all the necessary research domestically. Choice of the Collaborative approach assumes that the parties involved will be able to develop a program whose cost and schedule is acceptable to all, that major experimental facilities can be collaboratively built and operated, and that equitable allocation of research tasks and results can be arranged.

Advantages

Cost-Sharing.—The principal benefit of the Collaborative path is the cost-effective utilization of the resources available to the major fusion programs worldwide. Total funding now spent annually on fusion research throughout the world is comparable, or greater than, the amount needed per year to evaluate fusion's potential by the early 21st century. If the major fusion programs can minimize duplication of effort, reaching that evaluation should not require substantial budgetary increases in any of the major programs. Whereas pursuit of the Independent path requires doubling or tripling annual U.S. fusion budgets, the Collaborative path may only require funding increases of 20 to 50 percent above current levels.

Energy Supply.—If successfully implemented, the Collaborative approach would permit the United States and the other major fusion programs to evaluate fusion's potential by the early 21st century. The timing of this evaluation is similar—although possibly somewhat delayed—from that in the Independent path. However, the results of a Collaborative research effort would be more effectively shared among the major fusion programs.

Improving the Technical Base.—Fusion research may proceed more effectively if the research efforts of the major programs are integrated to a greater degree. All of the major programs have technical capabilities and skilled personnel that can contribute to the research and development effort. In addition, effective planning among the major fusion research programs can ensure that more research approaches are investigated. If, through such efforts, research efforts can be mutually supportive rather than duplicative, this widened technological base will benefit fusion research worldwide.

Foreign Policy Benefits.—The United States may wish to participate in a large-scale collaborative project for diplomatic reasons as well as technical ones. Since there appear to be significant technical and financial benefits to the United States from successful collaboration in fusion, diplomatic motivations would not appear to be in opposition to programmatic ones.

Disadvantages

Shared Control and Loss of Flexibility.—Under the Collaborative approach, the United States would sacrifice some control over the research program. International collaboration on the scale necessary for this approach will require compromise by all partners. In particular, some major experimental facilities, such as the International Experimental Thermonuclear Reactor, would probably not be sited in the United States. This approach could be less flexible than the others, since decisions—which would be made multilaterally—would be difficult to modify. Moreover, depending on how time-consuming the negotiation process is, the Collaborative path could take longer than the Independent path to develop fusion.

Obstacles to Large-Scale Collaboration.—If the potential obstacles to large-scale collaboration described in chapter 7 prove insurmountable, the Collaborative approach would fail. In this case, the United States would either have to make more resources available for fusion research, changing to the Independent path, or extend the schedule for fusion development as discussed in the Limited path (below).

Cost.—Although the cost of this approach is substantially less than that of proceeding independently, increases in U.S. annual fusion funding are nevertheless required to carry out this approach. If fusion research does not lead to an attractive energy source, this investment might be considered wasted.

Adverse Impact on Domestic Development.—The Collaborative approach is motivated in part by pressures to share costs and lessen research expenditures. However, if international collaboration is supported at the expense of maintaining a healthy domestic program, both the collaborative projects and the domestic program could be damaged. A viable domestic program is required to contribute to and be attractive for future collaboration.

The Collaborative approach may create tension between undertaking domestic activities, on the one hand, and participating in joint research with foreign programs, on the other. Incentives to minimize costs and avoid duplication will have to be balanced against developing and maintaining sufficient domestic expertise to contribute to and assimilate the results of collaborative projects.

THE LIMITED PATH

Description

Under the Limited path, fusion research would continue but would not be supported at the level necessary to evaluate fusion's potential domestically in the early 21st century. The schedule for developing fusion under this approach therefore would be delayed compared with the Independent or the Collaborative approaches. With the Limited path, funding levels would not be sufficient to support a healthy base program simultaneously with the construction of major facilities required to make progress in critical research areas.

Because there are so many different motivations for pursuing this approach, no single plan, strategy, or estimated funding level can adequately describe it. Clearly, the funding level would be less than that needed for the Independent path and more than that for the Mothballed path (below). It probably would be less than that needed for the Collaborative path, although even a funding profile sufficient for the Collaborative path would result in the Limited path if collaboration were found to be undesirable or unworkable.

The Limited approach would attempt to retain a base program in fusion research at universities and national laboratories. The program would be limited to scientific research, however, with funding levels and/or program intent not enabling it to advance to engineering development and demonstration. With the Limited path, fusion's scientific feasibility probably could be determined. It is unlikely, however, that engineering feasibility could be determined domestically, and commercial feasibility would be impossible to evaluate without increased financial support.

Motivations and Assumptions

With the Limited path, pursuit of fusion would not be a high national priority. Many different assumptions could result in a lower priority for fusion research and lead to selection of the Limited path. The Limited path also might be pursued as a "second choice" if either the Independent or the Collaborative approaches could not be sustained.

Assumptions that might lead to selection of the Limited approach include the judgment that fusion's promise or urgency was not high enough to justify the Independent approach but too high to warrant shutting the research program down entirely. Moreover, either the prospects or the rewards of international collaboration could be judged too low to pursue the Collaborative approach.

Perhaps the construction of large experimental facilities would not be seen as warranted unless or until further technological development—in or outside of the fusion program—brought down costs. Alternatively, it might be decided that while the near-term benefits of fusion research justified maintaining a limited program, the energy benefits did not justify a more extensive research effort. Delaying development of fusion's energy potential need not necessarily reduce the scientific, educational, and technological benefits of fusion research.

Advantages

Cost.—The major benefit of the Limited path is that the United States could maintain a limited research capability while still retaining the ability to accelerate fusion research at a later time. It would be cheaper—and therefore politically easier—to fund a Limited path program than the higher cost Independent or Collaborative approaches.

Flexibility.—In some ways, research with the Limited path may be more flexible than with either the Independent or Collaborative paths. Early design selections for large and expensive research facilities that would tend to lock in a given line of research emphasis would be avoided. Delaying these investments could make it possible to build them either at substantially lower cost or with a higher probability of commercial success.

Risk Avoidance.—Under this approach, the United States could let the rest of the world shoulder the expense and take the risk of determining fusion's feasibility. The United States would retain a base program in fusion research to preserve the expertise needed to evaluate and eventually reproduce work done abroad. The United States, of course, would start out with a competitive disadvantage in this case and might or might not be able to catch up. However, it would also be able to evaluate whether or not the technology was attractive without the substantial investments required to pursue the Independent or Collaborative paths. The United States would be free to attempt to develop an improved technology at some later time.

Disadvantages

Delaying Energy Supply.—The fundamental disadvantage of the Limited path is that it delays the evaluation of fusion. At our current level of understanding, experimental devices that are inherently large and expensive are required to resolve key uncertainties in the development of fusion power. Unless these facilities are funded, progress cannot be made and fusion's potential cannot be determined or developed.

Technical developments may ultimately decrease the cost or eliminate the need for expensive experiments. However, it is not likely that such developments will occur quickly enough for the Limited approach to make fusion power available on the same schedule as the Independent or Collaborative approaches. Moreover, significant developments may be less likely to occur or be recognized in the absence of a more ambitious research program.

Loss of Direction and Scope.—If the fusion research program is not targeted towards an evaluation of fusion's prospects as an energy source, it might become more of a basic science/plasma physics research program than an energy program. Without the direction provided by a relatively near-term goal—evaluating fusion's engineering feasibility—the program's subsequent evolution might lead it away from those issues that must be resolved to develop fusion reactors. This drift would not only delay the development of fusion power but might also make its eventual development less likely.

Damage to Fusion Infrastructure.—Limited Federal funding of fusion research could adversely affect many participants in the fusion research program. Industrial participation would be the most severely constrained; steady and predictable funding is required for industry to develop and maintain the capability to participate in fusion research. Depending on the funding level, national laboratories and universities might also have to cut back on fusion work.

Moreover, the field of fusion research in general and university programs in particular might not be able to attract the most talented students if the program were perceived as having an uncertain future. In this event, a valuable source of new ideas and innovation would be lost.

Loss of Momentum and International Stature.—With the Limited path, the fusion program could lose its momentum. Unless other countries also limited their programs, the United States would fall behind. If other countries successfully commercialized fusion technology, the United States could be at a competitive disadvantage, at least initially.

However, U.S. decisions and foreign decisions are not independent. Given that fusion research budgets are set in all the major fusion programs through a political process that balances fusion against other priorities, U.S. action to lower the priority of fusion research might weaken the positions of fusion researchers in other programs. Foreign fusion programs might reduce their research efforts. However, the other world fusion programs are clearly developing fusion for broader reasons than simply keeping up with the United States, and none of them are likely to eliminate their programs.

Difficulty in Collaboration.—If foreign fusion programs pursue research more aggressively than the United States, the United States may no longer be seen as a desirable collaborative partner.

THE MOTHBALLED PATH

Description

With the Mothballed path, the magnetic fusion research program would shut down. To capitalize on the research investment to date, this path would ideally be implemented in a manner that preserved the existing state of knowledge in the field and eased the transition of people and facilities from fusion to other areas. To keep open the option of restarting the fusion program in the future, some resources would be desirable (either provided directly or through other programs) to permit periodic reevaluation of fusion. Technical developments in other fields would have to be monitored, along with progress in alternate energy supply technologies, to see whether the decision to stop funding fusion research should be reviewed.

In practice, however, monitoring might be difficult. Competing funding priorities, too, might make it hard to acquire the resources needed to reevaluate a canceled program.

Motivations and Assumptions

Choosing the mothballed approach implies that development of fusion—even as a hedge—does not merit appreciable investment now or in the near future. Proponents of this approach might consider the current state of fusion technology analogous to that of computer technology in the 19th century: although many of the fundamental concepts were known, a century of technological progress in widely disparate fields was required before computers of any practical significance could be built.

Technological pessimism is not likely to be the deciding factor in stopping the fusion program, since the operation of CIT—if successful—should confirm the scientific feasibility of fusion. Instead, the decision to cancel the program probably would be motivated by the belief that fusion research will not result in a commercially, socially, or environmentally attractive source of energy, or that finding out how useful fusion could be is too expensive. The near-term benefits of conducting fusion research would not be assumed to justify the program, and the expected payoff of fusion would be considered too low to make cost-sharing with other countries attractive.

Advantages

Saving Money.—The major advantage of this approach would be avoiding the costs of future fusion research.

Disadvantages

Unavailability of Possible Energy Supply.—The major risk of this approach is that fusion's potential as an energy source would not be realized. Should future circumstances make reevaluating fusion desirable, restarting the program would be expensive, difficult, and time-consuming.

Destruction of Fusion Infrastructure.—With the Mothballed path, the people and facilities that currently carry out fusion research would switch to other programs; the associated benefits of fusion research such as personnel training, scientific research, and technological development would not continue in their current form. Although scientific data and technological accomplishments would not be lost, the "know-how" of individual researchers would be. Decades would be required from whenever a decision were made to resume the program until the earliest time that it could lead to a usable product. Dismantling the existing technological base and personnel pool does not irrevocably eliminate fusion as an option, but significant costs (in both time and resources) would be required to rebuild fusion research capability.

Mitigating this disadvantage somewhat is the breadth of plasma physics as a research discipline. Since plasma physics is intrinsic to many applications outside of fusion, plasma physics research and application would certainly persist through non-fusion-program sources, even if fusion research were discontinued. Although the areas of plasma physics most relevant to fusion would suffer, general plasma physics research could provide a core of expertise if a program restart were required.

Inhibiting Technical Development.—Without an extensive base of technical personnel trained in and sensitive to problems relevant to fusion, discoveries that might make fusion easier to achieve could go unrecognized.

Elimination of International Stature in Fusion.—If it is not conducting domestic fusion research, the United States will be unable to collaborate with other countries or benefit from the results of research done abroad. If fusion technology were developed successfully abroad, it could take many years for the United States to reproduce the technology.

Appendixes

Appendix A
Non-Electric Applications of Fusion[1]

The baseline D-T fusion reactor discussed in chapters 4 and 5 produces energetic neutrons as its immediate output. In an electric generating station, the energy of these neutrons would be recovered as heat and used to generate electricity. Other possible applications of D-T fusion technology might use the neutrons themselves to produce fission or fusion fuels or to induce nuclear reactions that change one isotope or material into another. Applications of fusion as a neutron source and other non-electric applications of fusion energy are discussed below.

Fusion as a Neutron Source

Each D-T reaction in the plasma produces one neutron, which is needed to breed tritium to replace that used in the reaction. However, additional neutrons can be generated by neutron multipliers in the reactor blanket.[2] These "excess neutrons" are available to make up for losses as well as for other purposes, such as the production of materials in the reactor blanket. Therefore, fusion reactors could be used as neutron sources in addition to sources of electricity.

If it produced a sufficiently valuable product, a fusion neutron source would not need to generate net electric power to be cost-effective. In practice, however, few if any such products exist; system studies show that a fusion reactor serving as a neutron source will probably also need to produce electric power to be economically viable. (A possible exception, tritium production, is discussed below.)

Fusion-reactor neutron sources could have significant advantages over fission reactors, the major existing large-scale sources of neutrons. A suitably designed fusion reactor would generate only about one-sixth the heat of a fission reactor with the same neutron output. Furthermore, the energy of the fusion neutrons is several times higher than the energy of fission neutrons, thus permitting applications that are not possible with fission.

Tritium Production

One application of a fusion-reactor neutron source would be production of tritium beyond that needed to fuel the fusion reactor.[3] As discussed in chapter 4, tritium self-sufficiency is a key issue for a fusion electric power reactor;[4] it is especially difficult to design a power-producing reactor capable of producing substantial amounts of excess tritium. However, tritium production can be enhanced at the expense of electricity generation.

Tritium has several industrial, medical, and military applications; its largest user is the nuclear weapons program. Tritium is radioactive, with 5.5 percent of the tritium stockpile decaying each year. Therefore, the tritium supply for nuclear weapons requires constant replenishment even if no additional weapons are built. Four fission reactors are operated for the Department of Energy (DOE) in Savannah River, South Carolina, to produce tritium for nuclear weapons. These reactors are currently about 35 years old, and they will soon need replacement.

A recent National Research Council study found that **although fusion reactors have promising features for breeding tritium, fusion technology is not yet sufficiently advanced to expand or replace the Savannah River facilities.**[5] The engineering development and testing needed to create reliable fusion tritium-breeders cannot be completed by the time decisions must be made concerning the Savannah River reactors. Nevertheless, the study also concluded that fusion has potential for producing tritium, and that DOE should "undertake a program that analyzes and periodically reassesses the concept, including design studies, experimentation, and evaluation, as fusion development proceeds."[6]

Fusion technology could be applied to tritium production without necessarily altering the technical course of the civilian magnetic fusion research program. However, if use of fusion technology for tritium production were to precede its commercial application as a civilian electricity generating technology, the fusion research program nevertheless could be profoundly affected. On one hand, the nuclear weapons program would shoulder some of the development costs and would provide a near-term motivation for supporting fusion research. Furthermore, associating fusion R&D with the nuclear weapons program would ensure it a higher national priority.

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[1] Much of the material in this appendix is drawn from K.R. Schultz, B.A. Engholm, R.F. Bourque, E.T. Cheng, M.J. Schaffer, and C.P.C. Wong, *The Fusion Applications and Market Evaluation—"FAME"—Study*, by GA Technologies, Inc., San Diego, CA, 1986. This study was done under contract to the Department of Energy's Office of Fusion Energy.

[2] Neutron multipliers are discussed in ch. 4, box 4-B.

[3] Tritium-producing fusion breeders are discussed in National Research Council, Committee on Fusion Hybrid Reactors, *Outlook for the Fusion Hybrid and Tritium-Breeding Fusion Reactors* (Washington, DC: National Academy Press, 1987), pp. 94-110. See the following section of this appendix for definitions and discussion of fusion hybrid reactors.

[4] See the section "The Fusion Blanket and First Wall" in ch. 4.

[5] National Research Council, *Outlook for the Fusion Hybrid and Tritium-Breeding Fusion Reactors*, op. cit., p. 16.

[6] Ibid.

On the other hand, **associating fusion power with the nuclear weapons program could also become a severe liability in terms of public acceptance**. Moreover, since the technical requirements for breeding tritium and producing electricity are different, features of the tritium-breeder design would not necessarily be applicable in an electric power reactor. The institutional experience gained in developing, building, and operating a military tritium-breeder may be even less transferable to a civilian power reactor than the technical experience because, at present, regulatory mechanisms for the two are so different.[7] For all of these reasons, adopting the technological or institutional framework from a military tritium-breeder to the civilian fusion program could seriously compromise the future acceptability of fusion power.

Fissionable Fuel Production or Use

In a *fission/fusion hybrid* reactor, excess fusion neutrons are used to breed fissionable fuel or to induce fission reactions within the fusion reactor blanket. There are, correspondingly, two different types of fission/fusion hybrid: one that uses fission reactions in its blanket to multiply the energy generated in the fusion core, and one that suppresses blanket fission reactions to generate fissionable fuel for use in pure fission reactors. The former type, the "power-only" hybrid, does not produce fissionable fuel. The latter, or "fission-suppressed" hybrid, does not produce much of its own power from fission reactions; instead, it transforms "fertile" materials that are not readily fissionable into fissionable fuels such as uranium or plutonium. In both types of hybrid, the total energy released (or made available) is much larger than that available from fusion reactions alone.[8]

Since most of the energy generated in a power-only hybrid is due to fission reactions, the amount of fusion power generated by such a device need not be large. Therefore, the fusion core of a power-only hybrid would not need to achieve as high a level of performance as the core of a pure fusion power reactor in terms of parameters such as energy gain.[9]

In combining the fusion process with fission, a hybrid reactor could also combine their liabilities. Since hybrid reactors involve the production and/or use of fissionable fuels, their environmental, safety, and proliferation concerns are more serious than those of pure fusion reactors; many of the environmental and safety concerns of nuclear fission, both perceived and actual, could be transferred to the hybrid. Furthermore, a complete evaluation of the fuel-producing hybrid must include the client fission reactors. **If the incentive for pursuing fusion research is to provide an energy alternative that is environmentally or socially preferable to nuclear fission, then combining fusion with fission in a fission/fusion hybrid reactor might not accomplish that goal**.

The economic justification for hybrid reactors is weak at present because the price of uranium fuel is so low. According to the National Research Council hybrid study, uranium prices must rise by a factor of between 6 and 20 for a fission/fusion hybrid to be economically attractive.[10] The study concluded that accelerated use of fission reactors in the United States, coupled with policy decisions requiring U.S. reactors to be fueled with domestic uranium supplies, could increase the domestic price of uranium by a factor of 10 by the year 2020. However, a more likely rate of fission growth would cause prices to reach this level sometime between 2020 and 2045, and relaxing the constraint on domestic supply would delay such a price increase for an additional 30 years. Therefore, the NRC study concluded that fission/fusion hybrids will probably not be economically justified in terms of increased uranium price before the middle of the next century.

Several additional factors besides the price of uranium affect the economic viability of fission/fusion breeders. First, advanced-converter fission reactors that use uranium much more efficiently than present light-water reactors would be less sensitive than present reactors to the price of uranium. Development of these more efficient reactors would further delay the time when breeders would become attractive. Second, any discussion of hybrid breeders must compare them to pure fission breeders, which can also produce fissionable fuel. Such a comparison is beyond the scope of this study.

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[7] Weapons-related DOE facilities are not now subject to the same process of Nuclear Regulatory Commission and National Environmental Policy Act review that governs civilian nuclear facilities. However, public pressure for increasing the regulation of military reactors is growing.

[8] Energy multiplication occurs because a fission reaction releases about 10 times as much energy as a fusion reaction. Each excess neutron that induces a fission reaction in the blanket releases many times more energy than it originally carries. (The same energy multiplication occurs when fissionable material produced in a fusion reactor is removed to fuel external reactors, except that the additional energy is released in the external reactors and not in the fusion blanket.)

[9] Energy gain is discussed in the section of ch. 4 titled "Scientific Progress."

[10] National Research Council, *Outlook for the Fusion Hybrid and Tritium-Breeding Fusion Reactors*, op. cit., p. 8. The study estimated fission/fusion breeders to become economically viable when the price of uranium oxide reaches from $100 to $300 per pound; the price currently is $17 per pound.

Other Isotope Production

With the possible exception of tritium and fissionable fuels, no materials have yet been identified that would justify building a fusion reactor for the sole purpose of producing them. To be economically worthwhile, high-value materials would have to be produced from inexpensive ones through reactions with fusion neutrons. In addition, extraction of the desired isotope from the fusion blanket could not be too expensive. Furthermore, the amount of the material produced in a fusion reactor must not be so large compared to the demand that it would saturate the market, driving down the price and destroying the value of the material.

It would be much easier to justify producing special materials or isotopes in a fusion reactor if electricity were produced at the same time. A recent study has identified cobalt-60 (^{60}Co) as an isotope that might be economically produced in a fusion electric generating station.[11] However, demand for ^{60}Co would have to be much greater than it is now for this process to be viable, since the amount of ^{60}Co that could be produced annually in a single fusion reactor is much larger than the present annual demand.

Cobalt-60 is an intensely radioactive material whose primary use is in sterilizing medical products, with secondary uses in providing cancer radiation therapy and food preservation via irradiation. Food preservation, in particular, could be a rapidly growing application. Furthermore, ^{60}Co also could be used to treat sewage by sterilizing it, although this application has yet to be commercialized. It is possible, therefore, that ^{60}Co demand might increase substantially.[12]

The worldwide demand for replenishing existing ^{60}Co stocks is currently estimated to be about 11 megacuries per year,[13] most of which is produced by Atomic Energy of Canada, Ltd. in the heavy-water moderated CANDU reactors operated by Ontario Hydro. A commercial fusion power reactor could produce hundreds of megacuries of ^{60}Co per year with a blanket optimized for ^{60}Co production. Therefore, this application is viable only at greatly increased demand levels; depending on its increased use for food preservation, the annual growth in this demand over the next several years has been estimated at 6 to 25 percent.[14]

Radioactive (Fission) Waste Processing

In theory, the neutrons from a fusion reactor could be used to change radioactive fission wastes into shorter lived materials that would decay more quickly, posing less long-term hazard. However, **several studies in the 1970s analyzed fusion's capabilities to process radioactive waste from fission reactors, and the results were not promising.**[15] These studies determined that extremely high levels of fusion reactor performance and decades of neutron irradiation would be required, along with advanced isotope and chemical separation processes. Even if these requirements were met, it was unclear whether this approach offered a net advantage over waste burial. The benefit of reducing the long-term hazard associated with fission wastes would have to be balanced against the technological difficulties associated with transforming them, as well as the short-term risk of releasing these wastes in an accident at the processing facility.

Other Possible Non-Electric Applications of Fusion

Synthetic Fuels

Currently, about two-thirds of all energy used in the United States is consumed directly by users in the form of fossil fuel; only one-third is used to generate electricity. Although the trend in future energy use is towards increasing electrification, many requirements for non-electric sources of energy such as liquid or gas fuels will likely remain.

It may be possible to take advantage of the high temperatures present in fusion reactors, along with the electricity generated by them, to generate hydrogen gas by decomposing water into hydrogen and oxygen. Hydrogen has applications either directly as a fuel or in the synthesis of liquid fuels. The GA fusion applications study indicated that fusion might be an economically competitive source of hydrogen in the long term but did not demonstrate a clear advantage over high-temperature fission-based sources of hydrogen that could also be available by the time fusion is commercialized.

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[11] B.A. Engholm, E.T. Cheng, and K.R. Schultz, "Radioisotope Production in Fusion Reactors," GA Technologies Inc., San Diego, CA (undated). This article was prepared as part of the "Fusion Applications Study" by K.R. Schultz, et al., 1986.

[12] Ibid., p. 2.

[13] One curie of any radioactive substance is the amount that produces 3.7×10^{10} radioactive disintegrations per second; 1 megacurie is 1 million curies. One curie of pure ^{60}Co would have a mass of 0.88 milligram, and 11 megacuries would have a mass of 9.7 kilograms (21 pounds). (Actual ^{60}Co sources do not consist of pure ^{60}Co; in practice, less than 10 percent of the cobalt in a ^{60}Co source consists of the ^{60}Co isotope.) In 1984, the price of ^{60}Co was about $1.00 per curie. (Ibid., pp. 2-3.)

[14] Ibid., p. 3.

[15] For a review of these studies, see Schultz, et al., *Fusion Applications Study*, op. cit., pp. 9-10.

Process Heat

Another energy requirement currently satisfied by non-electric sources of energy is process heat. Process heat is less transportable than electricity; it must be used at locations close to the generating site. Moreover, although there are many users of process heat, few require more than a few hundred megawatts each. Essentially all of these users now use fossil fuels. Present fusion reactor designs would produce on the order of 3,000 megawatts of heat (corresponding to 1,000 to 1,200 megawatts of electricity at 35- to 40-percent conversion efficiency), and there would be little motivation to construct such a fusion plant dedicated solely to the production of process heat. There does not even appear to be significant economic advantage associated with recovering waste heat produced as a byproduct of electricity generation. **Process heat does not appear to be an attractive use for fusion reactors as long as fossil fuels are available.** This conclusion is supported by present-day experience with nuclear fission powerplants, which are not used for process heat production in the United States. In the far future, if fossil fuels become too expensive or too difficult to use in an environmentally sound manner, fusion could become attractive as a source of process heat due to lack of an alternative.

Appendix B

Other Approaches to Fusion

The main body of this report has discussed magnetic confinement fusion, the approach to controlled fusion that the worldwide programs emphasize most heavily. However, two other approaches to fusion are also being investigated. All three approaches are based on the same fundamental physical process, in which the nuclei of light isotopes, typically deuterium and tritium, release energy by fusing together to form heavier isotopes. Some of the technical issues are similar among all the fusion approaches, such as mechanisms for recovering energy and breeding tritium fuel. However, compared to magnetic confinement, the two approaches discussed below create the conditions necessary for fusion to occur in very different ways, and some substantially different science and technology issues emerge in each case.

Inertial Confinement Fusion[1]

The inertial confinement approach to fusion research has been studied for some two decades, and its current budget almost half that of the magnetic confinement program. In inertial confinement fusion, a pellet of fusion fuel is compressed to a density many times that of lead, and then heated and converted to plasma, by bombarding it with laser or particle beams (see figure B-1). At this density, about 10 billion times the density of a magnetically confined plasma, the confinement time needed is so small (less than one-billionth of a second) that it should be possible to generate net fusion power before the pellet blows itself apart. The pellet's own *inertia* is sufficient to hold it together long enough to generate fusion power.

Inertial confinement already has been demonstrated on a very large scale in the hydrogen bomb, an inertially confined fusion reaction whose input energy is provided by a fission (atomic) weapon. The challenge of laboratory-scale inertial confinement research is to reproduce this process on a much smaller scale, with a source of input energy other than a nuclear weapon. In a hypothetical inertial confinement reactor, microexplosions with explosive yields equivalent to about one-tenth of a ton of TNT would be generated by irradiating fusion pellets—called *targets*—with laser or particle beams; these explosions would be repeated several times a second.

The issues addressed by inertial confinement fusion research in the United States concern the individual targets containing the fusion fuel; the input energy sources, called *drivers*, that heat and compress these targets; and the mechanism by which energy from the driver is delivered—or coupled—into the target. Due to the close relationship between inertial confinement fusion target design and thermonuclear weapon design, inertial confinement fusion research is funded by the nuclear weapons activities portion of the Department of Energy's (DOE's) budget. Inertial confinement research is conducted largely at nuclear weapons laboratories; its near-term goals are dedicated largely to military, rather than energy applications, and a substantial portion of this research is classified.

There are two near-term military applications of inertial confinement fusion—one actual and one not yet realized. First, because the physical processes in a pellet micro-detonation resemble those in a nuclear weapon, inertial confinement experiments now contribute to validating computer models of these processes, to collecting fundamental data on the behavior of materials in nuclear weapons, and to developing diagnostic instruments for actual nuclear weapons tests. These activities can be conducted today with existing high-energy inertial confinement drivers.

These applications could be greatly intensified, and a second set of applications would arise, if a laboratory facility producing substantial pulses of inertially confined fusion energy could be developed. No such facility yet exists. Such a facility could simulate the effects, particularly the radiation effects, of nuclear detonations on systems and components. This application might be particularly important if a Comprehensive Test Ban Treaty prohibited underground tests of nuclear weapons.

The near-term, military inertial confinement research effort also contributes information that would be essential to any longer term commercial applications. For example, both military and civilian applications of inertial confinement fusion (other than the computer program and diagnostic development activities that are being conducted today) require that an inertial confinement target generate several times more energy than is input to it. Such an accomplishment, which would show the scientific feasibility of inertial fusion, is beyond the capability of any existing laboratory device. (Of course, thermonuclear weapons have already demonstrated the scientific feasibility of very-large-scale inertial confinement fusion.)

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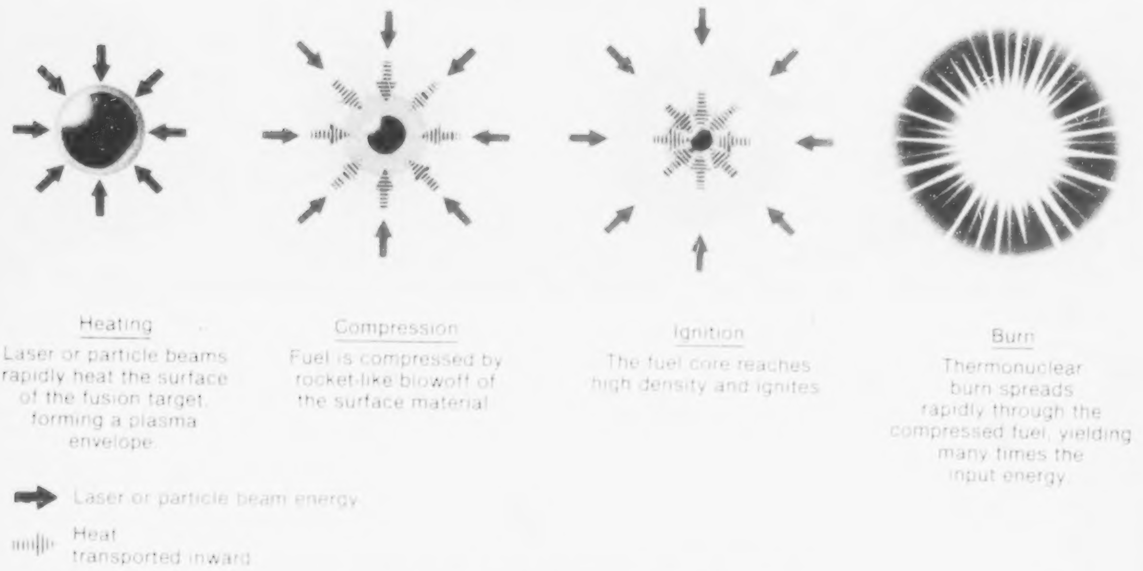
[1] The U.S. inertial confinement fusion research program is reviewed in a recent report by the National Research Council, *Review of the Department of Energy's Inertial Confinement Fusion Program* (Washington, DC: National Academy Press, 1986).

Figure B-1.—Inertial Confinement Fusion Process


Heating
Laser or particle beams rapidly heat the surface of the fusion target, forming a plasma envelope.
Compression
Fuel is compressed by rocket-like blowoff of the surface material
Ignition
The fuel core reaches high density and ignites
Burn
Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.
Laser or particle beam energy
Heat transported inward

SOURCE: Lawrence Livermore National Laboratory, "ICF Reaction," *Energy and Technology Review*, April-May 1986

The technical requirements for commercial applications of inertial confinement fusion go considerably beyond the requirements for weapons effect simulation and would require still further scientific and technological development. Due to the relatively low efficiencies (e.g., 10 to 25 percent) at which the drivers operate, each target explosion must generate several times more energy than it is driven with to reach breakeven. An additional factor of 4 to 10 is required beyond breakeven to produce substantial net output. In a commercial reactor, therefore, as much as 100 times as much energy must be released in a pellet explosion as is required to heat and compress the pellet to the point where it can react. Furthermore, commercial energy production requires that pellets be detonated several times a second, far more frequently than needed for military applications. Finally, cost-effectiveness, reliability, and high efficiency are much more important for energy applications than military ones; successful commercialization will depend on how well the technology addresses the commercial requirements discussed in chapter 5.

A significant potential advantage of inertial confinement over magnetic confinement is that the complex and expensive driver system can be located some distance away from the reaction chamber. Because radiation, neutron-induced activation, and thermal stress due to the microexplosions could be largely confined to the reaction chamber, the driver would not have to be designed to withstand this environment. In the core of a magnetic confinement fusion reactor, on the other hand, systems both for supporting and maintaining the plasma and for recovering the energy and breeding tritium fuel are located in high radiation, high neutron-flux environments. A second potential advantage of inertial confinement arises from the relatively relaxed vacuum requirements inside the reaction chamber, which would permit the use of neutron absorbing materials such as liquid lithium inside the first structural wall of the reactor. Use of such neutron absorbers would lessen neutron irradiation levels in the reactor's structural elements, increase the lifetimes of those elements, and lessen induced radioactivity levels.

On the other hand, inertial confinement also has disadvantages compared to magnetic confinement. Inertial confinement is inherently pulsed; the systems needed to recover energy and breed fuel in the reaction chamber have to withstand explosions equivalent to a few hundred pounds of TNT several times a second. Inertial confinement reactors must focus high-power driver beams precisely on target in this environment. Furthermore, the energy gains needed for these facilities must be much larger than those of a magnetic confinement device to make up for driver inefficiencies.

Four principal driver candidates are now being studied in the U.S. inertial confinement research program. Two of them—*solid-state* or *glass lasers* and *light-ion*[2] *accelerators*—have by far the largest facilities; the other two principal candidates—*gas lasers* and *heavy ion accelerators*—are in lesser stages of development. Major U.S. glass lasers are located at Lawrence Livermore National Laboratory in California and the University of Rochester Laboratory for Laser Energetics in New York. The Livermore facility, the most powerful laser in the world, does both classified and unclassified inertial confinement research; the University of Rochester facility conducts only unclassified research on a laser fusion approach that is not as relevant to weapons applications as is the approach pursued at Livermore. The largest light-ion accelerator in the world is located at Sandia National Laboratory in New Mexico; like the Livermore facility, it conducts both unclassified and classified research. The krypton-fluoride gas laser, the third driver candidate being studied, is being developed at Los Alamos National Laboratory. Other contributors to the laser and light-ion inertial confinement programs are the Naval Research Laboratory and KMS Fusion, Inc., the only private corporation significantly involved.

A fourth driver candidate—the heavy-ion accelerator—is much less developed than the laser or light-ion drivers. Unlike light-ion and laser research, heavy-ion accelerator research is a non-military program funded by the Office of Energy Research, the same DOE office that funds the magnetic confinement fusion program.[3] Heavy-ion experimental work is limited to accelerator technology, and in the United States it is concentrated at Lawrence Berkeley Laboratory in California.

Other national fusion programs conduct inertial confinement research, but at a significantly lower level of effort than their magnetic fusion programs. International collaboration is much more restricted in inertial fusion than it is in magnetic fusion due to U.S. national security constraints. **On balance, the inertial confinement program involves scientific and technological issues that are quite distinct from those relevant to magnetic fusion. A detailed comparison of the relative status and prospects of inertial confinement and magnetic confinement fusion is beyond the scope of this assessment**.

Cold Fusion

Another approach to fusion, presently at an embryonic stage of development, is fundamentally different from either the magnetic or inertial confinement concepts. This approach, called "cold fusion" or "muon-catalyzed fusion," might make it possible to bypass the requirement for extremely high temperatures that make the magnetic and inertial approaches so difficult.[4]

If it were possible to "shield" the electric charge of one of the nuclei in a fusion reaction, one nucleus could get very close to another nucleus without being repelled. In this case, fusion reactions could occur at far lower temperatures than would otherwise be required, since the extreme temperatures needed to overcome the mutual repulsion of two electrically charged nuclei would be unnecessary. Such shielding can in fact be provided by a subatomic particle called the *muon*. The muon—like the electron—has a charge that cancels out the charge of a hydrogen nucleus. But unlike the electron, the muon binds so tightly to the nucleus that the nuclear charge is shielded even down to the distances where fusion reactions can take place. Therefore, once a muon becomes bound to a nucleus, the combination can approach a second nucleus closely enough to fuse without the need for extreme temperature.

If the muon is freed in the subsequent fusion reaction, it can become captured by another hydrogen nucleus to repeat the process. In this way it serves as a *catalyst*, enabling fusion energy to be released without itself being consumed. However, since the muon is unstable, muon catalysis can be practical only if each muon generates more than enough energy during its 2.2-microsecond lifetime to make its own replacement.

Muon-catalyzed fusion reactions were actually observed in high-energy physics experiments in the 1950s. However, the muons were rarely observed to induce more than one fusion reaction each before decaying, compared to the hundreds of reactions per muon that would be necessary to make the process worthwhile. More recent experimental and theoretical work has shown that the number of fusion reactions that can be catalyzed by a single muon depends on parameters such as the density and temperature of the deuterium-tritium mixture into which the muon is injected. Experiments have shown that muons are capable of catalyzing many more reactions during their lifetime than had been thought many years ago.

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[2] Light ions are ions of light elements such as lithium.

[3] The heavy-ion research program is far smaller than the magnetic confinement program and is managed by a different part of the DOE Office of Energy Research.

[4] A discussion of recent muon-catalyzed fusion research is given in "Cold Nuclear Fusion," by Johann Ratelski and Steven E. Jones, in the July 1987 issue of *Scientific American*, pp. 84-89.

Whether this process can ever yield net energy production depends on increasing the number of fusion reactions per muon. The number is not yet high enough for the process to be scientifically feasible, and fundamental limits may prevent it from ever being so. Muon-catalysis research, currently at a very preliminary stage, focuses primarily on understanding the limits to how many fusion reactions can be induced by a single muon. If muon-catalysis proves to be feasible in principle, a substantially increased level of effort and a more detailed comparison of its potential benefits and liabilities to those of the other fusion approaches may be warranted.

Appendix C

Data for Figures

Chapter Three

Data for Figure 3-1.—Historical Fusion Funding, 1951-88 (millions of 1986 dollars)

Year	Budget authority	Operating		Capital equipment		Construction	
		Budget authority	Index	Budget authority	Index	Budget authority	Index
1951-53	1.1	1.1	0.200	[a]		[a]	
1954	1.8	1.8	0.202	[a]		[a]	
1955	6.1	4.7	0.203	[a]		1.4	0.162
1956	7.4	6.6	0.202	[a]		0.8	0.167
1957	11.6	10.7	0.205	[a]		0.9	0.175
1958	29.2	18.4	0.212	[a]		10.8	0.182
1959	28.9	27.0	0.218	[a]		1.9	0.189
1960	33.7	31.0	0.220	2.2	0.260	0.5	0.196
1961	30.0	29.0	0.224	1.0	0.260	[a]	
1962	24.8	23.0	0.226	1.8	0.261	[a]	
1963	25.5	24.2	0.228	1.3	0.262	[a]	
1964	22.6	21.0	0.231	1.6	0.263	[a]	
1965	23.1	21.3	0.234	1.8	0.266	[a]	
1966	23.1	21.8	0.238	1.3	0.269	[a]	
1967	23.9	22.4	0.243	1.5	0.276	[a]	
1968	26.6	24.7	0.252	1.8	0.285	0.1	0.247
1969	29.7	26.5	0.263	1.6	0.295	1.6	0.264
1970	34.3	27.7	0.277	2.0	0.305	4.6	0.284
1971	32.2	28.3	0.291	2.1	0.319	1.8	0.310
1972	33.3	31.0	0.310	2.1	0.327	0.2	0.344
1973	39.7	37.0	0.320	2.5	0.334	0.2	0.368
1974	57.4	52.9	0.353	4.3	0.351	0.2	0.393
1975	118.2	97.9	0.382	19.8	0.376	0.5	0.444
1976	166.3	131.1	0.429	17.0	0.489	18.2	0.484
TQ[b]	52.9	42.6	0.429	4.5	0.489	5.8	0.484
1977	316.3	195.0	0.459	23.0	0.518	98.3	0.516
1978	332.4	206.7	0.493	29.6	0.568	96.1	0.564
1979	355.1	211.3	0.529	27.2	0.619	116.6	0.613
1980	350.3	235.1	0.588	29.8	0.684	85.4	0.675
1981	393.6	258.3	0.674	36.9	0.777	98.5	0.746
1982	451.2	295.1	0.766	42.0	0.847	114.1	0.814
1983	461.3	373.8	0.829	39.5	0.893	48.0	0.865
1984	468.4	391.1	0.892	37.8	0.947	39.5	0.882
1985	429.6	369.6	0.938	27.5	0.954	32.5	0.934
1986	361.5	320.5	1.000	28.3	1.000	12.7	1.000
1987 (estimate)	327.3	302.2	1.043	17.1	1.051	8.0	1.025
1988 (request)	320.1	286.1	1.080	18.1	1.088	15.9	1.060

[a] No expenditures occurred in this category during the year.

[b] The start of the fiscal year was charged in 1976 from July 1 to October 1. TQ represents the budget for the transition quarter from July 1, 1976 to September 30, 1976.

SOURCE: U.S. Department of Energy, Office of Energy Research, letter to OTA project staff, Aug. 15, 1986; updated by personal communication to OTA staff, Sept. 2, 1987.

Data for Figure 3-2.—Historical Fusion Funding, 1951-88 (millions of current dollars)

Year	Presidential budget request budget authority	Total budget authority (in millions)	Year	Presidential budget request budget authority	Total budget authority (in millions)
1951-53	[a]	1.1	1972	[a]	33.3
1954	[a]	1.8	1973	[a]	39.7
1955	[a]	6.1	1974	[a]	57.4
1956	[a]	7.4	1975	102.3	118.2
1957	[a]	11.6	1976	144.2	166.3
1958	[a]	29.2	TQ[b]	44.4	52.9
1959	[a]	28.9	1977	291.1	316.3
1960	[a]	33.7	1978	370.9	332.4
1961	[a]	30.0	1979	334.0	355.1
1962	[a]	24.8	1980	364.1	350.3
1963	[a]	25.5	1981	403.6	393.6
1964	[a]	22.6	1982	460.0	451.2
1965	[a]	23.1	1983	444.1	461.3
1966	[a]	23.1	1984	467.0	468.4
1967	[a]	23.9	1985	482.7	429.6
1968	[a]	26.6	1986	390.0	361.5
1969	[a]	29.7	1987 (estimate)	333.0	341.4
1970	[a]	34.3	1988 (request)	345.6	
1971	[a]	32.2			

[a] Presidential budget requests before 1975 were not available from DOE

[b] The start of the fiscal year was charged in 1976 from July 1 to October 1. TQ represents the budget for the transition quarter from July 1, 1976 to September 30, 1976.

SOURCE: U.S. Department of Energy, Office of Energy Research, letter to OTA project staff, Aug. 15, 1986

Chapter Six

Data for Figure 6-1.—Federal Funding of Plasma Physics in 1984 (millions of 1984 dollars)

Plasma Physics Area	DOE	NSF	DoD	NASA	NOAA	Total
General Plasma Physics	3	3	68	0	0	74
Magnetic Conf. Fusion	471	0	0	0	0	471
Inertial Conf. Fusion	170	0	0	0	0	170
Space/Astrophysical Plasma	2	30	5	100	2	139
Total	646	33	73	100	2	854

DOE = Department of Energy
NSF = National Science Foundation
DoD = Department of Defense
NASA = National Aeronautics and Space Administration
NOAA = National Oceanic and Atmospheric Administration

SOURCE: National Research Council, *Physics Through the 1990s: Plasmas and Fluids* (Washington, DC: National Academy Press, 1986), p. 33.

Data for Figure 6-2.—Defense and Civilian Federal Research and Development Expenditures (billions of current dollars)

Year	Defense	Civilian	Total
1982	22.9	15.8	38.7
1983	25.6	14.4	40.0
1984	30.5	15.5	46.0
1985	34.7	17.0	51.7
1986	37.6	17.0	54.6
1987 (estimate)	41.2	18.6	59.8
1988 (request)	48.1	21.3	69.4

NOTE: Defense: includes Department of Defense along with Department of Energy atomic energy defense activities. Civilian: includes all Federal research and development not included in defense.

SOURCE: American Association for the Advancement of Science, *AAAS Report XII: Research and Development FY 1988* (Washington, DC: American Association for the Advancement of Science, 1987).

Data for Figure 6-3.—Major Components in Federally Funded Research and Development (in 1987 dollars) and Figure 6-4.—Historical Component Funding Levels for Federal Research and Development (billions of current dollars)

Year	Defense	Energy	Space	Health	Science	Other
1982	22.9	3.5	3.6	4.1	1.5	3.1
1983	25.6	2.9	1.7	4.5	1.6	3.7
1984	30.5	2.6	2.0	5.1	1.9	3.9
1985	34.7	2.5	2.4	5.8	2.1	4.2
1986	37.6	2.4	1.9	5.9	2.1	4.7
1987 (estimate)	41.2	2.2	2.4	7.0	2.2	4.8
1988 (request)	48.1	2.0	3.1	9.0	2.6	4.7

NOTE: Defense includes Department of Defense along with Department of Energy atomic energy defense activities. Energy includes Department of Energy activities less general science and defense, Nuclear Regulatory Commission, and Environmental Protection Agency. Space includes National Aeronautics and Space Administration less space applications and aeronautical research. Health includes Department of Health and Human Services, Veterans Administration, Department of Education, and Environmental Protection Agency. Science includes National Science Foundation and Department of Energy high energy physics and nuclear physics.

SOURCE: American Association for the Advancement of Science, *AAAS Report XII: Research and Development FY 1988* (Washington, DC: American Association for the Advancement of Science, 1987).

Data for Figure 6-5.—Annual Appropriations of DOE Civilian Research and Development Programs (millions of current dollars)

Year	Solar/renewables[a]	Fusion	Fission	Fossil	Conservation
1980	731.4	350.3	847.8	847.8	296.1
1981	711.2	393.6	817.0	821.3	292.5
1982	341.1	451.2	819.4	566.8	151.9
1983	261.2	461.3	701.7	310.9	133.5
1984	211.9	468.4	622.9	[illegible]	150.1
1985	201.7	429.6	412.6	[illegible]	175.5
1986 (estimate)	[illegible]	361.5	358.1	343.0	170.9
1987 (estimate)	146.3	341.4	329.3	451.0	160.7
1988 (request)	93.5	345.6	336.4	368.5	80.1

[a] Solar/Renewables includes Solar, Geothermal, and Hydroelectric programs.

SOURCE: **Fusion**—U.S. Department of Energy, Office of Energy Research, letter to OTA project staff, Aug. 15, 1986. **Others**—"Analysis of Trends in Civilian R&D Appropriations for the U.S. Department of Energy," prepared by Argonne National Laboratory, August 1986, table B.3, p. 49.

Data for Figure 6-6.—Major DOE Civilian Research and Development Funding at National Laboratories in Fiscal Year 1987 (millions of 1987 dollars)

Solar and Other Renewables	$114.5
Electric Systems	19.6
Environment	133.3
Conservation	49.5
Fossil Energy	116.6
Supporting Research	360.0
Nuclear Energy	254.3
Magnetic Fusion	245.6

SOURCE: U.S. Department of Energy, *FY 1988 Congressional Budget Estimates for Laboratory/Plant*, January 1987.

Chapter Seven

Data for Figure 7-1.—Comparison of International Fusion Budgets (current dollars) and Figure 7-2.—Comparison of International Equivalent Person-Years

United States:

Year	Fusion budget (in millions $)	Average industrial hourly wage ($)	Person-years
1980	350.3	7.27	23,165
1981	393.6	7.99	23,683
1982	451.2	8.50	25,520
1983	461.3	8.84	25,088
1984	468.4	9.16	24,584
1985	429.6	9.57	21,582
1986	361.5	10.04	17,310

Japan:

Year	Fusion budget (yen)	Fusion budget (in millions $)	Average industrial hourly wage (yen)	Average industrial hourly wage ($)	Person-years
1980	52,256	230	1,293	5.70	19,430
1981	61,115	277	1,373	6.22	21,400
1982	72,025	289	1,225	5.72	24,300
1983	69,112	291	1,490	6.28	22,300
1984	60,392	251	1,561	6.50	18,600
1985	65,154	271	1,640	6.83	19,100
1986	64,861	381	1,704	10.02	18,300

European Community:

Year	Fusion budget (MECU)	Fusion budget (in millions $)	Average industrial hourly wage ($)	Person-Years
1980	190	264	5.93	21,404
1981	225	254	5.35	22,815
1982	300	297	5.20	27,457
1983	300	300	5.06	28,532
1984	350	298	4.60	31,086
1985	350	245	4.06	28,977
1986	375	338	5.60	28,990

SOURCE: U.S. Department of Energy, Office of Energy Research, staff memorandum to file, Oct. 9, 1986

Data for Figure 7-3.—Comparison of International Fusion Budgets by Percentage Gross National Product[a]

Year	United States		European Community		Japan	
	GNP	Fusion/GNP	GNP[b]	Fusion/GNP	GNP	Fusion/GNP
1980	2,632	0.0133	1,962	0.0135	899	0.0271
1981	2,958	0.0133	2,131	0.0119	964	0.0287
1982	3,069	0.0147	2,277	0.0130	1,060	0.0273
1983	3,305	0.0139	2,394	0.0125	1,138	0.0256
1984	3,363	0.0128	data unavailable		data unavailable	

[a] All Gross National Products are shown in billions of current dollars.

[b] The GNP for the European Community is computed by adding the GNP's of the major EC countries (Belgium, France, Federal Republic of Germany, Greece, Italy, Netherlands, and the United Kingdom).

SOURCE: Gross National Products found in *Statistical Abstract*, No. 1742.

Appendix D

List of Acronyms and Glossary

Acronyms

AEC —Atomic Energy Commission

ASDEX-U —Axisymmetric Divertor Experiment Upgrade; Garching, Federal Republic of Germany

ATF —Advanced Toroidal Facility; Oak Ridge National Laboratory, Oak Ridge, Tennessee

CERN —European Laboratory for Nuclear Research (after its original French acronym)

CIT —Compact Ignition Tokamak; proposed for the Princeton Plasma Physics Laboratory, Princeton, New Jersey

COCOM —Coordinating Committee

CPMP —Comprehensive Program Management Plan

CPRF —Confinement Physics Research Facility; under construction at Los Alamos National Laboratory, Los Alamos, New Mexico

D III —Doublet III; GA Technologies Inc., San Diego, California

D III-D —Doublet III Upgrade; GA Technologies, San Diego, California

D-D Reaction —Deuterium-deuterium fusion reaction (see Glossary)

D-T Reaction —Deuterium-tritium fusion reaction (see Glossary)

DoD —U.S. Department of Defense

DOE —U.S. Department of Energy

dpa —displacements per atom

EC —European Community

ECRH —electron cyclotron resonance heating (see Glossary)

EPRI —Electric Power Research Institute; Palo Alto, California

ERAB —Energy Research Advisory Board

ERDA —Energy Research and Development Administration

ESECOM —Senior Committee on Economic, Safety, and Environmental Aspects of Magnetic Fusion Energy

ETR —engineering test reactor (see Glossary)

eV —electron volt (see Glossary)

FED —Fusion Engineering Device

FER —Fusion Experimental Reactor (proposed Japanese engineering test reactor)

FPA —Fusion Power Associates; Gaithersburg, Maryland

FRC —field-reversed configuration (see Glossary)

GA —GA Technologies Inc.; San Diego, California

GNP —gross national product

IAEA —International Atomic Energy Agency

ICRH —ion cyclotron resonance heating (see Glossary)

IEA —International Energy Agency

IFF —Integrated Fusion Facility

INTOR —International Tokamak Reactor

ITER —International Thermonuclear Experimental Reactor

JAERI —Japan Atomic Energy Research Institute

JET —Joint European Torus; Abingdon, UK

JIFT —Joint Institute for Fusion Theory; University of Texas at Austin, Texas, and Nagoya University in Japan

JT-60 —Japan Tokamak-60

LANL —Los Alamos National Laboratory; Los Alamos, New Mexico

LCT —Large Coil Task; Oak Ridge National Laboratory, Oak Ridge, Tennessee

LLNL —Lawrence Livermore National Laboratory; Livermore, California

LMFBR —liquid metal fast breeder reactor (fission—see Glossary)

LWR —light-water reactor (fission—see Glossary)

MFAC —Magnetic Fusion Advisory Committee

MFECC —Magnetic Fusion Energy Computing Center; Lawrence Livermore National Laboratory, Livermore, California

MFEE Act —Magnetic Fusion Energy Engineering Act of 1980 (Public Law 96-386)

MFPP —Magnetic Fusion Program Plan

MFTF-B —Mirror Fusion Test Facility B at Lawrence Livermore National Laboratory, Livermore, California

MIT —Massachusetts Institute of Technology; Cambridge, Massachusetts

NASA —U.S. National Aeronautics and Space Administration

NET —Next European Torus (proposed European engineering test reactor)

NIH —U.S. National Institutes of Health

NRC —U.S. Nuclear Regulatory Commission

NSF —U.S. National Science Foundation

OER —Office of Energy Research in the U.S. Department of Energy

OFE —Office of Fusion Energy in the Office of Energy Research, U.S. Department of Energy
OHTE —Ohmically Heated Toroidal Experiment; GA Technologies Inc., San Diego, California
ORNL —Oak Ridge National Laboratory; Oak Ridge, Tennessee
OTR —Operational Test Reactor (proposed Soviet engineering test reactor)
PBX-M —Princeton Beta Experiment Modification; Princeton Plasma Physics Laboratory, Princeton, New Jersey
PPPL —Princeton Plasma Physics Laboratory; Princeton, New Jersey
Q —Energy Gain (see Glossary)
RF —radiofrequency
RFP —reversed-field pinch (see Glossary)
TEXT —Texas Experimental Tokamak; University of Texas Fusion Research Center in Austin, Texas
TEXTOR —Tokamak Experiment for Technology Oriented Research; Julich, Federal Republic of Germany
TFTR —Tokamak Fusion Test Reactor; Princeton Plasma Physics Laboratory, Princeton, New Jersey
TMX —Tandem Mirror Experiment; Lawrence Livermore National Laboratory, Livermore, California
TMX-U —Tandem Mirror Experiment Upgrade; Lawrence Livermore National Laboratory, Livermore, California
Tokamak —Toroidal magnetic chamber, in Russian (see Glossary)
TPA —Technical Planning Activity
TSTA —Tritium Systems Test Assembly; Los Alamos National Laboratory, Los Alamos, New Mexico
UCLA —University of California at Los Angeles
UFA —University Fusion Associates
UK —United Kingdom

Glossary

Acid deposition: A consequence of fossil fuel combustion in which combustion byproducts emitted as gases react in the atmosphere and are deposited on earth in the form of acidic substances. Also called "acid rain."

Activation product: Material made radioactive through exposure to neutrons in fission or fusion reactors.

Active protection: The condition in which the safety of a nuclear reactor can be assured only through the proper design and operation of active safety systems. See "Passive protection."

Advanced tokamak: A tokamak incorporating features such as steady-state current drive or shaping of the plasma in order to attain higher performance or more efficient operation than the conventional tokamak. See "Tokamak" or "Conventional tokamak."

Afterheat: Heat produced by the continuing decay of radioactive atoms in a nuclear reactor after fission or fusion reactions have stopped. Afterheat in a fission reactor originates primarily in the fuel rods; in a fusion reactor it would result mainly from induced radioactivity in the reactor structure.

Alpha particle: A positively charged particle, identical to a helium-4 nucleus, composed of two protons and two neutrons. An alpha particle is emitted in the radioactive decay of many naturally occurring radioisotopes such as uranium and thorium; it is also one of the products of the D-T fusion reaction.

Alternate confinement concept: A fusion magnetic confinement concept other than the tokamak.

Anomalous transport: Loss of energy from tokamak plasmas due to escaping electrons that occurs at a rate several times higher than that predicted by present theory.

Ash: The end-product of a fusion reaction. For the D-T fusion reaction, the "ash" is helium gas.

Atom: A particle of matter indivisible by chemical means that is the fundamental building block of a chemical element. The dense inner core of the atom, called the nucleus, contains protons and neutrons and constitutes almost all the mass of the atom. The nucleus is surrounded by a cloud of orbiting electrons. Atoms contain equal numbers of positively charged protons and negatively charged electrons and as a whole are electrically neutral. An atom is a few billionths of an inch in diameter, and several sextillion (1 followed by 21 zeros) atoms are found in an ordinary drop of water.

Atomic nucleus: See "Nucleus."

Auxiliary heating: External systems that heat plasmas to higher temperatures than can be reached from the heat generated by electric currents within the plasma. Neutral beam heating and radiofrequency heating are both examples of auxiliary heating systems.

Axial: The direction in a cylinder parallel to the central axis of the cylinder.

Background radiation: Naturally occurring sources of radiation. Primary sources are cosmic rays and naturally occurring radioactive isotopes that are found in the earth or are produced in the atmosphere by cosmic rays.

Balance of plant: Those systems in a fusion reactor not associated with producing or controlling the fusion reaction. Systems in the balance of plant convert the heat produced by fusion reactions into electricity. See also "Fusion power core."

Beta: The ratio of the outward pressure exerted by the plasma to the inward pressure that the magnetic confining field is capable of exerting. Beta is equivalent to the ratio of the energy density of particles in the plasma to the energy density of the confining magnetic fields.

Beta particle: A high-energy electron emitted in the decay of certain radioactive isotopes.

Bilateral agreement: An agreement between two nations.

Biologically active: Substances that are absorbed by living organisms and are utilized in biological processes. Radioactive substances that are biologically active (e.g., radioactive iodine or strontium isotopes) become incorporated into living organisms.

Blanket: Structure surrounding the plasma in a fusion reactor within which the fusion-produced neutrons are slowed down, heat is transferred to a primary coolant, and tritium is bred from lithium.

Breakeven: The point at which the fusion power generated in a plasma equals the amount of heating power that must be added to the plasma to sustain its temperature.

Breakeven-equivalent: Attainment in a non-tritium-containing plasma of conditions (temperature, density, and confinement time) that would result in breakeven if the plasma contained tritium. Because plasmas not containing tritium are far less reactive than those containing tritium, the actual amount of fusion power generated by a breakeven-equivalent plasma will be far less than would be produced under actual breakeven conditions.

Breeder reactor: A nuclear reactor that produces more fissionable fuel than it consumes. Breeders produce fissionable fuel by irradiating fertile materials with neutrons. See "Fertile material."

Breeding ratio: The number of tritium atoms produced in the blanket of a fusion reactor for each tritium atom consumed in the fusion plasma.

Burn control: The mechanism by which the power level of a self-sustaining fusion reaction is regulated.

Capital-intensive: An energy-generating technology in which most of the cost of energy is due to the fixed cost of the capital investment in the generating station, as opposed to variable fuel or operations and maintenance expenditures.

Carbon dioxide (CO_2): An inherent product of the combustion of fossil fuels. Buildup of carbon dioxide in the earth's atmosphere as a result of fossil fuel use may affect global climate. See "Greenhouse effect."

Central cell: In the tandem mirror confinement concept, the central cell is the region where most of the power-producing fusion reactions would occur. Plasma in the central cell is kept from escaping by electric fields generated by the end cells. See "End

Centrifugal injector: Device that uses centrifugal force to inject pellets of frozen fuel into fusion plasmas.

Chlorofluorocarbons: Manmade chemicals, used as refrigerants, industrial solvents, and for other purposes, which have heat-retaining properties similar to carbon dioxide when released into the atmosphere.

Cladding: In a fission reactor, the material that encloses nuclear fuel.

Classical confinement: The best possible plasma confinement, in which the only mechanism by which particles escape the plasma is through rare, but inevitable, collisions between plasma particles that cause them to migrate across the magnetic field towards the plasma edge. Classical confinement is also referred to as "classical diffusion."

Classification: Restricting the dissemination of certain information for reasons of national security. Only people holding security clearances granted by the government are permitted access to classified information.

Closed confinement concept: Magnetic configuration in which the plasma is confined by magnetic lines of force that do not lead out of the device. Closed confinement concepts all have the basic shape of a doughnut or inner tube, which is called a torus.

Collaboration: An intensive type of international cooperation involving a substantial degree of program integration, funding commitment, and joint management.

Commercial feasibility: Fusion power's acceptance in the marketplace as a source of energy that is environmentally and socially acceptable and economically competitive when compared to alternate sources of energy.

Compact toroids: A class of magnetic confinement configurations in which the chamber containing the plasma need not have a central hole through which external magnet coils must pass. Examples are the spheromak and the field-reversed configuration.

Compression heating: Method of heating a plasma by compressing it into a smaller volume. The plasma is compressed by modifying the external magnetic fields.

Conceptual design: The basic or fundamental design of a fusion reactor or experiment that sketches out device characteristics, geometry, and operating features but is not at the level of detail that would permit construction.

Confinement: Restraint of plasma within a designated volume. In magnetic confinement, this restraint is accomplished with magnetic fields.

Confinement concept: A particular configuration of magnetic fields used to confine a fusion plasma. Various confinement concepts differ in the shape of their magnetic fields and in the manner in which these fields are generated.

Confinement parameter: The product of plasma density and confinement time that, along with temperature, determines the ratio between power produced by the plasma and power input to the plasma. Also called "Lawson parameter."

Confinement time: A measure of how well the heat in a plasma is retained. The confinement time of a plasma is the length of time it would take the plasma to cool down to a certain fraction of its initial temperature if no heat were added.

Confining magnets: External magnets used to generate the confining magnetic fields in a fusion device.

Containment building: In a fission reactor, the containment building is a thick concrete structure surrounding the pressure vessel that encloses the reactor core and other components. It is designed to prevent radioactive material from being released to the atmosphere in the unlikely event that anything should escape from the pressure vessel. The need for containment buildings for fusion reactors has not yet been determined.

Conventional tokamak: A tokamak device not incorporating advanced steady-state current drive or plasma shaping technology. See "Tokamak," "Advanced tokamak."

Coolant: Fluid that is circulated through a component or system to remove heat. In a fusion reactor, the coolant would flow through the blanket to remove the heat generated by fusion reactions.

Cooperation: In the context of international activities, cooperation refers to all activities involving nations or individuals from different nations working together.

Critical temperature: The temperature below which a superconducting material loses all resistance to electricity. See "Superconductivity."

Curie: A unit of radioactivity. One curie of a radioactive substance is that amount that undergoes 3.7×10^{10} (37 billion) nuclear transformations per second.

D-D reaction: Fusion reaction in which one nucleus of deuterium fuses with another. Two different outcomes are possible: a proton plus a tritium nucleus, or a neutron plus a helium-3 nucleus.

D-T reaction: Fusion reaction in which a nucleus of deuterium fuses with a nucleus of tritium, forming an alpha particle and a neutron and releasing 17.6 million electron volts of energy. The D-T reaction is the most reactive fusion reaction.

Decay heat: See "Afterheat."

Decommissioning: The steps taken to render a plant, particularly a nuclear reactor, safe to the environment at the end of its operating lifetime.

Dense z-pinch: An open confinement concept in which a strong electrical current is suddenly passed through a fiber of frozen D-T fuel, turning it into a plasma and at the same time generating a powerful encircling magnetic field to confine the plasma. The dense z-pinch is in a very preliminary stage of development.

Density: Amount per unit volume. By itself, the term "density" often refers to particle density, or the number of particles per unit volume. However, other quantities such as energy density or power density (energy or power per unit volume, respectively) can also be defined.

Detritiation systems: Systems to remove tritium from air or water that are important to ensure the safety of tritium-handling facilities.

Deuterium (D or ^{2}H): A naturally occurring isotope of hydrogen containing one proton and one neutron in its nucleus. Approximately one out of 6,700 atoms of hydrogen in nature is deuterium. Deuterium is one of the fuels (along with tritium) needed for the D-T fusion reaction, the most reactive fusion reaction.

Diagnostics: The procedure of determining (diagnosing) exactly what is happening inside an experimental device during an experiment. Also, the instruments used for diagnosing.

Diffusivity: The ability of a substance, especially a gas, to diffuse through another substance.

Direct conversion techniques: Conversion of the kinetic energy of plasma particles directly into electrical energy without first converting it into heat. Since conversion into heat and the subsequent reconversion to electricity impose inherent inefficiencies, direct conversion could improve the efficiency of a fusion generating station.

Divertor: A component of a toroidal fusion device used to shape the magnetic field near the plasma edge so that particles at the edge are diverted away from the rest of the plasma. These particles are swept into a separate chamber where they strike a barrier, become neutralized, and are pumped away. In this way, energetic particles near the plasma edge are captured before they can strike the walls of the main discharge chamber and generate secondary particles that would contaminate and cool the plasma. Divertors have also been found to be responsible for establishing a mode of enhanced tokamak confinement called the "H-mode." See "H-mode scaling."

Driven fusion reactor: A fusion reactor operating below breakeven that must be driven with more energy than it produces. Such a reactor might serve to generate neutrons for a fusion materials test facility.

Electromagnetic radiation: Radiation consisting of associated and interacting electric and magnetic fields that travel in a wave at the speed of light. Radio waves, microwaves, light, x-rays, and gamma rays are all forms of electromagnetic radiation; they differ from one another in wavelength and frequency.

Electron: An elementary particle with a unit negative electrical charge and a mass 1/1837 that of a proton. In an atom, electrons surround the positively charged nucleus and determine the atom's chemical properties.

Electron cyclotron frequency: The frequency at which electrons in a plasma gyrate about magnetic field lines. The electron cyclotron frequency increases with increasing magnetic field strength and is typically hundreds of gigahertz, substantially higher than the ion cyclotron frequency. See also "ion cyclotron frequency."

Electron cyclotron resonance heating (ECRH): A process in which only electrons gain energy from an applied radiofrequency field operating at the electron cyclotron frequency. The electrons then heat other plasma particles through collisions.

Electron temperature: The temperature of the electrons in a plasma. Electron temperature can differ from ion temperature. Some of the mechanisms by which energy is lost from the plasma, in particular radiation losses, depend on electron temperature.

Electron volt (eV): A unit of energy equal to the energy that can be acquired by singly charged particle (e.g., an electron) from a one-volt battery. Since the temperature of a system is proportional to the average energy of each particle in the system, temperature is also measured in electron volts; at a temperature of 1 eV, equal to 11,605° K, the average energy of each particle is roughly 1 eV. As a unit of energy, one eV equals 1.602×10^{-19} Joule, 3.827×10^{-20} calorie, 1.519×10^{-22} Btu, or 4.45×10^{-26} kilowatt-hour.

End cell: In the tandem mirror confinement concept, the end cell is a magnetic mirror used to plug each end of the central cell. The function of the end cell is to generate an electric field that will keep the plasma in the central cell from leaking out. See also "Central cell."

Energy gain (Q): The ratio of the fusion power produced by a plasma to the amount of power that must be added to the plasma to sustain its temperature.

Engineering feasibility: The ability to design and construct all the components, systems, and subsystems required for a fusion reactor.

Engineering test reactor: A next-generation fusion experiment to study the physics of long-pulse ignited plasmas, provide opportunities to develop and test reactor blanket components under actual fusion conditions, and integrate the various systems of a fusion reactor.

Equivalent Q: For a plasma not containing tritium, a measure of what Q would have been in a tritium-containing plasma that attained the same temperature and confinement parameter. See "Confinement parameter."

External heating: See "Auxiliary heating."

External magnets: Magnet coils outside the fusion plasma that generate those confining magnetic fields that are not generated by currents within the plasma itself.

Fast breeder reactor: A fission reactor in which fast neutrons are used both to induce fission reactions in the fuel, producing power, and to react with fertile materials, converting them to more fissile fuel. See "Fast neutron," "Fertile material," and "Fissile material."

Fast neutron: A neutron with energy greater than 100,000 electron volts.

Fertile material: Material that is not fissile but can be converted to fissile material through neutron irradiation. See "Fissile material."

Field-reversed configuration (FRC): A magnetic confinement concept with no toroidal field, in which the plasma is essentially cylindrical in shape. The FRC is a form of compact toroid.

Financial liability: Costs, including those associated with death, injury, property damage, and loss of revenue, to which an electric utility would be exposed in the event of the worst credible accident attributable to a generating station.

Fine-scale plasma instabilities: Turbulence and other instabilities occurring over distances the size of the orbits of individual plasma particles (electrons and ions) about magnetic field lines. Also called "microinstabilities."

First wall: The first physical boundary that surrounds the plasma. The first wall can refer either to the surface of the blanket that faces the plasma, or to a separate component between the blanket and the plasma.

Fissile material: Material that can be used as fuel in fission reactors.

Fission: The process by which a neutron strikes a nucleus and splits it into fragments. During the process of nuclear fission, several neutrons are emitted at high speed, and heat and radiation are released.

Fission/fusion hybrid: A reactor using a fusion core to produce neutrons that in turn either induce fission reactions or breed fissile fuel in the reactor blanket. Fission/fusion hybrid reactors can produce energy, fissile fuel, or both.

Flux: The amount of a quantity (heat, neutrons, etc.) passing through a given area per unit time.

Fossil plant: A powerplant fueled by coal, oil, or gas.

Fusion: The process by which the nuclei of light elements combine, or fuse, to form heavier nuclei, releasing energy.

Fusion power core: That portion of a fusion reactor containing all the systems having to do specifically with the fusion process, such as the plasma chamber, the blanket, the magnets, and the heating, fueling, and impurity control systems.

Fusion self-heating: Heat produced within a plasma from fusion reactions. Since alpha particles produced in fusion reactions remain trapped within the plasma, they contribute to self-heating by transferring their energy to other plasma particles in collisions. Fusion-produced neutrons, on the other hand, escape from the plasma without reacting further and do not contribute to self-heating.

Gauss: A measure of magnetic field strength. The strength of the earth's magnetic field on the earth's surface is about one-half gauss; magnetic confinement fusion devices typically have maximum magnetic field strengths of tens of thousands of gauss.

Gigahertz: A measure of frequency equal to 1 billion hertz, or 1 billion cycles per second. See "Hertz."

Gravitational confinement: The fusion process that occurs in the sun and other stars in which fusion plasmas are confined by the gravitational fields generated by their own masses. Enormous masses (considerably more than that of the planet Jupiter) are required for gravitational confinement.

Greenhouse effect: Possible warming of the earth due to excess heat trapped in the atmosphere by increasing levels of carbon dioxide and other "greenhouse gases."

Greenhouse gases: Gases such as chlorofluorocarbons, methane, nitrous oxide, and carbon dioxide that, in the upper atmosphere, have the property of retaining heat that would otherwise escape from the earth to space. Accumulation of such gases may affect global climate. See "Greenhouse effect."

"H-mode" scaling: A mode of tokamak behavior in which confinement time does not degrade as increased amounts of auxiliary power are used to heat the plasma. This scaling has been observed in tokamaks that have divertors, and it is believed to be closely related to conditions at the edge of the plasma. See "L-mode scaling."

Half-life: The time required for one-half of the atoms of an unstable radioactive element to decay into atoms of other substances. Each radioisotope has a unique half-life, which can range from fractions of a second to billions of years.

Heads-of-state agreement: An agreement between nations signed by their respective heads-of-state. For the United States, the head-of-state is the President.

Heat exchanger: A device for transferring heat from one fluid to another without allowing them to mix. Heat exchangers are used in nuclear reactors to transfer heat out of the reactor core without circulating the coolant, which becomes radioactive, through the rest of the generating station.

Heat load: The amount of heat that a reactor component must withstand. Both the choice of materials for the component and the amount of cooling that must be provided to it depend on the component's anticipated heat load.

Helium nucleus: See "Alpha particle."

Hertz: One cycle per second; a measure of frequency.

High energy gain: A fusion reaction producing many (10 or so) times as much power as must be input to the reaction to maintain its temperature.

High-level waste: Radioactive waste that is extremely radioactive and would pose a serious health and environmental risk if released into the environment. Disposal of high level waste must minimize the possibility of its release.

Hydrogen (H): The lightest element. All hydrogen atoms have nuclei containing a single proton and have a single electron orbiting that nucleus. Three isotopes of hydrogen exist, having 0, 1, or 2 neutrons in their nuclei in addition to the proton. The term hydrogen is also used to refer to the most common isotope, technically called "protium," that has no neutrons in its nucleus.

Ignition: The point at which a fusion reaction becomes self-sustaining. At ignition, fusion self-heating is sufficient to compensate for all energy losses; external sources of heating power are no longer necessary to sustain the reaction.

Impurities: Atoms present in a plasma that are heavier than fusion fuel atoms. Impurities are undesirable because they dilute the fuel and because they increase the rate at which the plasma's energy is radiated out of the plasma.

Induced radioactivity: Radioactivity created when non-radioactive materials are bombarded by neutrons and become radioactive. Radioactivity can be induced in essentially any material by exposure to neutrons, but the half-life and intensity of this radioactivity depends strongly on the material.

Industrial base: The industrial capability to design and manufacture the components of a fusion plant, to construct such plants, and to accomplish the preprocessing and reprocessing of fuels.

Inertia: Inertia is the property of an object to resist external forces that would change its motion. Unless acted upon by external forces, an object at rest will remain at rest, and an object moving in a straight line at constant speed will continue to do so. Under the influence of external forces, objects with differing inertias will respond at different rates. The inertia of an object depends solely on its mass.

Inertial confinement: An approach to fusion in which intense beams of light or particles are used to compress and heat tiny pellets of fusion fuel so rapidly that fusion reactions occur before the pellet has a chance to expand. The pellet's own inertia, or its initial resistance to expansion even when it is being blown apart, holds the pellet together long enough for fusion energy to be produced.

Information exchange: Sharing technical approaches and experimental data through any or all of several channels, including meetings, conferences, symposia, workshops, and publication in technical journals.

Inherent safety: In this report, inherent safety is the ability to assure, solely through reliance on passive systems and laws of physics, that no immediate off-site fatalities can result from any mechanical malfunction, operator error, or natural disaster. True inherent safety can be assured only by having so little hazardous material that even complete release could not cause an off-site prompt fatality, or by having so little stored energy that even if all the stored energy were released at once, the resultant explosion or fire would not be powerful enough to disperse a fatal dose of hazardous material. See "Active protection" and "Passive protection."

Instabilities: Small disturbances that become amplified, or become more intense, once they begin. A cone balanced upside-down on its tip is subject to an instability, since once it begins to wobble, it will become more unbalanced until it falls over. A stable system, on the other hand, responds to disturbances bv opposing them. Small disturbances in a stable system decrease in intensity until they die away. If a ball sitting in the bottom of a bowl is disturbed, for example, it will eventually come to rest again at the bottom of the bowl.

Insulator: Material that does not conduct electricity.

Ion: An atom (or molecularly bound group of atoms) that has become electrically charged as a result of gaining or losing one or more orbital electrons. A completely ionized atom is one stripped of all its electrons.

Ion cyclotron frequency: The frequency at which ions in a plasma gyrate about magnetic field lines. The ion cyclotron frequency increases with increasing magnetic field strength and is typically tens to hundreds of megahertz. See also "electron cyclotron frequency."

Ion cyclotron resonance heating (ICRH): A process in which only ions gain energy from an applied radiofrequency field operating at the ion cyclotron frequency. The ions then heat other plasma particles through collisions.

Ion temperature: The temperature of the ions in a plasma. Ion temperature can differ from electron temperature. Since it is the ions that fuse in fusion reactions, it is the ion temperature that determines the fusion reaction rate. See also "Electron temperature."

Ionization: The process of removing or adding an electron to a neutral atom, thereby giving it an electric charge and creating an ion. The term is also used to denote removal of an electron from a partially ionized atom to make a more completely ionized one.

Ionizing radiation: Radiation energetic enough to ionize matter that it passes through. Depending on its intensity, ionizing radiation poses a health risk. Examples are alpha and beta particles, emitted by radioactive substances, and electromagnetic radiation having frequencies in the far ultraviolet, x-ray, and gamma ray regions.

Isotope: Different forms of the same chemical element whose atoms differ in the number of neutrons in the nucleus. (All isotopes of an element have the same number of protons in the nucleus and the same number of electrons orbiting the nucleus.) Isotopes of the same element have very similar chemical properties and are difficult to separate by chemical means. However, they can have quite different nuclear properties.

Joint construction and operation: Pooling resources to construct and operate an experimental facility jointly.

Joint planning: Activities between nations that coordinate experimental and theoretical programs and identify areas of future cooperative research.

Joint research: Making major national facilities available to researchers from other nation's programs in exchange for financial or technical contributions.

Kinetic energy: Energy of motion. The energy released in a fusion reaction is originally in the form of kinetic energy of the reaction products. When these reaction products (alpha particles and neutrons) collide with atoms or nuclei in the plasma or in the reactor structure, they slow down and their kinetic energy is converted into heat.

"L-mode" scaling: Mode of tokamak behavior in which confinement time degrades as increasing amounts of auxiliary heating power are input into the plasma. See "H-mode" scaling.

Large-scale plasma instabilities: Deformations of both the overall confining magnetic field and the plasma that can lead to sudden escape of the entire plasma from confinement.

Laser fusion: A form of inertial confinement fusion in which a small pellet of fuel material is compressed and heated by a burst of laser light. See "Inertial confinement."

Lawson parameter: See "Confinement parameter."

Light-water reactor (LWR): A fission reactor in which ordinary water is used as coolant and as a neutron moderator. See "Neutron moderator."

Limiter: Device placed inside the plasma chamber to intercept particles at the edge of a plasma. By "scraping off" these particles from the plasma edge, the limiter defines the size of the plasma.

Liquid-metal fast breeder reactor: (LMFBR) A fission fast breeder reactor with a liquid metal coolant. See "Fast breeder reactor."

Lithium (Li): A light, chemically reactive metal that can be converted in the blanket of a fusion reactor into the tritium fuel needed for fusion reactions.

Load change, capability for: The mechanical and thermal characteristics of an electric generating station that limit its rate of response to changes in load or that restrict the time required for startup or shutdown.

Long-lived radioactivity: Radioactive isotopes having long half-lives.

Low-activitation materials: Materials that, under neutron irradiation, do not generate intensely radioactive, long-lived radioactive isotopes. Examples include certain vanadium alloys and ceramics such as silicon carbide. Fusion reactors made of low-activation materials would accumulate far less radioactivity over their lifetimes than reactors made with more conventional materials such as steels. Low-activation materials also produce less afterheat following a reactor shutdown than more conventional materials. See "Afterheat."

Low-level waste: Waste containing sufficiently low levels of radioactivity that it does not pose a major health or environmental risk. Disposal of low-level waste does not require the stringent precautions necessary for high-level waste.

Magnetic confinement: Any means of containing and isolating a hot plasma from its surroundings by using magnetic fields.

Magnetic field: The property of the space near a magnet that results, for example, in the attraction of iron to the magnet. Magnetic fields are characterized by their direction and their strength. Electrically charged particles moving through a magnetic field at an angle with respect to the field are bent in a direction perpendicular to both their direction of motion and the direction of the field. Particles moving parallel to a magnetic field are not affected. Therefore, magnetic fields cannot prevent plasma particles from escaping along field lines.

Magnetic field line: A (possibly curved) line whose direction at every point is given by the direction of the magnetic field through that point. Electrically charged particles in a magnetic field tend to gyrate around magnetic field lines; they can travel along the field lines much more easily than they can cross field lines.

Magnetic mirror: A generally axial magnetic field that has regions of increased intensity at each end where the magnetic field lines converge. These regions of increased intensity "reflect" charged particles traveling along the field lines back into the central region of lower magnetic field strength.

Magnetohydrodynamics (MHD): The study of electrically conducting fluids under the influence of electric and magnetic fields. MHD theory can be used to provide a good approximation to plasma behavior in many instances.

Megahertz: One million hertz, or one million cycles per second. See "Hertz."

Microinstabilities: See "Fine-scale plasma instabilities."

Minimum-B mirror: An open magnetic confinement concept with a magnetic field that is low in strength in the central region but that gets stronger in all directions away from the center. Particles in a minimum-B mirror tend to be "reflected" by the higher field regions back towards the center. Nevertheless, losses from the minimum-B mirror are too great for it to be a viable fusion concept by itself.

Minimum load: The power output level below which a generating plant cannot operate continuously.

Ministerial agreement: An agreement signed by the secretaries or ministers of the involved departments or ministries. In the United States, ministerial agreements in fusion are signed by the Secretary of Energy.

Multilateral agreement: An agreement between three or more nations.

Neutral beam heating: Heating a confined plasma by injecting beams of energetic (typically greater than 100 keV) neutral atoms into it. Neutral atoms can cross magnetic lines of force to enter the plasma, where they transfer their energy to plasma particles through collisions. In these collisions, the neutral beam particles become ionized, and, like the other electrically charged plasma particles, are then confined by the magnetic fields.

Neutron: A basic atomic particle, found in the nucleus of every atom except the lightest isotope of hydrogen, that has no electrical charge. When bound within the nucleus of an atom, the neutron is stable. However, a free neutron is unstable and decays with a half-life of about 13 minutes into an electron, a proton, and a third particle called an antineutrino. The mass of a free neutron is 1.7×10^{-24} grams.

Neutron flux: A measure of the intensity of neutron irradiation. It is the number of neutrons passing through 1 square centimeter of a given target in 1 second.

Neutron irradiation: Exposure to a source of neutrons. Both fission and fusion reactors can provide neutron irradiation.

Neutron moderator: A material that slows neutrons down without absorbing them.

Neutron multiplier: A substance that reacts with neutrons to produce additional neutrons.

Neutron wall loading: The energy per unit area per unit time (or energy flux) carried by neutrons into the first wall of a fusion reactor. The higher the neutron wall loading, the more rapidly the first wall will suffer radiation damage, the more radioactivity will be induced, and the more frequently first wall components will have to be replaced.

Non-ohmically heated plasma: Plasma heated with auxiliary or external heating.

Nuclear fission: See "Fission."

Nuclear fusion: See "Fusion."

Nuclear grade: Designation given to components used in important safety-related systems in nuclear reactors certifying that the components meet stringent quality control standards.

Nuclear physics: The study of atomic nuclei and nuclear reactions.

Nucleus (nuclei): The central core of an atom, consisting of protons and neutrons, that contains over 99.95 percent of the atom's mass.

Ohmic heating: Heating that occurs when an electric current is passed through a resistive medium. Although plasmas are excellent conductors of electricity, they are nevertheless resistive enough to be heated when they carry large electric currents. Ohmic heating becomes less efficient as the plasma gets hotter, and most confinement configurations therefore require auxiliary (or non-ohmic) heating to reach ignition.

Open confinement concept: Magnetic configuration in which the magnetic field lines leave the system. The magnetic mirror is one example.

Order of magnitude: A factor of 10.

Outage rate: The percentage of time that an electric generating station is unavailable due to component failures or other unforeseen conditions that require the unit to be removed from service.

Overnight construction cost: Total construction cost of a facility if it could be built instantaneously. Overnight construction cost does not include allowances for inflation, nor does it include finance charges such as the interest payments on funds borrowed to begin construction.

Oxidation chemistry: Study of chemical reactions of substances with oxygen.

Part-load efficiency: The ratio of the change in efficiency of an electric generating station to the change in load when the load is decreased from full load to half.

Particle collisions: A close approach of two or more particles during which quantities such as energy, momentum, or charge are exchanged.

Passive protection: Ability to ensure the safety of a reactor without the use of active safety systems. Various degrees of passive protection exist. At one level, the safety of a reactor design might be ensured provided that certain passive systems and components (e.g., coolant loops or tanks) remained intact. Before the safety of such a plant could be demonstrated, it would have to be proven that no credible accident could interfere with the operation of those passive systems or components. At a much more stringent level of passive protection, called "Inherent safety," materials properties and the laws of physics alone would be sufficient to ensure the safety of the reactor. No assumptions concerning the integrity of any reactor systems or components would need to be made. Such an "inherently safe" reactor would remain safe even if it could somehow be crumpled up into a ball. See also "Active protection" and "Inherent safety."

Personnel exchange: The transfer of personnel between different nation's programs through visits or assignments.

Plant capital cost: The total cost necessary to bring the plant to commercial operation. It includes the costs of items such as engineering and design work, materials, construction labor, construction management, interest during construction, escalation, sales tax, equipment, and land.

Plant licensability: How readily a generating technology such as fusion can be expected to receive regulatory approval.

Plant life: The total time a plant can be operated before decommissioning.

Plasma: An ionized gaseous system composed of approximately equal numbers of positively and negatively charged particles and variable numbers of neutral atoms. The charged particles interact among themselves, with the neutral particles, and with externally applied electric and magnetic fields. The plasma state is sometimes called "the fourth state of matter" due to the fundamental differences in behavior between plasmas and solids, liquids, or neutral gases.

Plasma current: Electrical current flowing within a plasma. In many confinement schemes, plasma currents generate part of the confining magnetic fields.

Plasma exhaust: Particles escaping from the plasma that are collected by limiters or divertors.

Plasma physics: The study of plasmas.

Plant safety: The capability of the plant to be built and operated with minimal injury to plant personnel or to the public and minimal damage to property internal or external to the plant.

Plutonium (Pu): An element that fissions easily and can be used as a nuclear fuel for fission reactors or fission weapons. Plutonium is not found in nature, but it can be produced by irradiating uranium with neutrons in a nuclear reactor.

Pneumatic injector: Device that injects fuel pellets into plasmas at high speed by accelerating them with compressed gas.

Poloidal direction: On a torus, the poloidal direction runs around the torus the short way, perpendicular to the toroidal direction. See "Toroidal direction."

Poloidal divertor: A type of divertor. See "Divertor."

Post-shutdown systems: Systems in a nuclear reactor that must operate after the reactor is shut down to ensure that the afterheat does not build up to a level high enough to damage the reactor or pose a safety hazard. Such systems would be unnecessary in reactors not generating much afterheat, or ones in which the afterheat could be removed by purely passive means.

Power density: The amount of energy generated per unit time per unit volume of a reactor core; the power per unit volume.

Project Sherwood: The code-name under which fusion research was secretly conducted in the United States from 1951 until 1958.

Proliferation: The development of nuclear weapons by countries not now possessing them. Proliferation refers primarily to fission-based nuclear weapons.

Prompt fatalities: Deaths due to the immediate effects of a reactor accident or malfunction. Since deaths from radiation overdoses are not instantaneous except at extremely high doses, prompt fatalities include those due to radiation overdoses acquired soon after an accident even if death does not occur immediately. Prompt fatalities do not, however, include deaths many years later from cancer that may have been induced by radiation exposure.

Proof-of-concept experiment: Experiment done at a relatively early stage of development of a confinement concept to determine the limits of plasma stability, explore how the confinement properties appear to scale, and develop heating, impurity control, and fueling methods. Successful completion of such an experiment verifies that the confinement concept appears capable of operating successfully on a scale much closer to that needed in a reactor.

Proof-of-principle experiment: Experiment one stage beyond the "proof-of-concept" stage to determine optimal operating conditions, to establish that the concept is capable of being scaled to near-reactor level, to extend methods of heating to high power levels, and to develop efficient mechanisms for fueling and impurity control.

Protium (H or ^{1}H): The most common isotope of hydrogen, accounting for over 99 percent of all hydrogen found in nature. The nucleus of a protium atom is a single proton with no neutrons.

Proton: An elementary particle with a single positive electrical charge. Protons are constituents of all atomic nuclei. The atomic number of an atom is equal to the number of protons in its nucleus.

Pulsed operation: Non-continuous operation of a fusion reactor. This term refers to reactors that must periodically stop and restart. In pulsed operation, individual pulses may last as long as hours.

Pumped limiter: A limiter that collects particles at the plasma edge, allows them to recombine into neutral gas atoms, and pumps the gas out of the vacuum chamber. A pumped limiter can operate for a longer period of time than a simple limiter, which does not remove the collected particles and can therefore become saturated. See "Limiter."

Pure fusion reactor: Reactor that generates all its energy from fusion reactions in the plasma and tritium-breeding reactions in the blanket. A pure fusion reactor is distinguished from a fission/fusion hybrid reactor, which either generates energy or produces fissionable fuel by including fertile or fissile material in the reactor blanket. See "Fission/fusion hybrid."

Quality of confinement: See "Confinement parameter."

Radiation: The emission of particles or energy from atomic or nuclear processes. Radiation is also sometimes used as a shorthand for "electromagnetic radiation," which refers specifically to emitted energy and does not include particles.

Radiation dose: A general term denoting the quantity of radiation absorbed.

Radiation exposure: The amount of radiation passing through a particular target.

Radiative cooling: Loss of heat from a system through electromagnetic radiation. Since electromagnetic radiation carries energy away, a system that radiates will cool down.

Radioactive inventory: The total amount of radioactive material present.

Radioactive material: A material of which one or more constituents exhibits radioactivity.

Radioactivity: The inherent property of the nuclei of unstable isotopes to spontaneously emit particles or energy and transform to other nuclei. Such radioactive isotopes can be either natural (e.g., carbon-14, which is produced by cosmic rays interacting with the earth's atmosphere) or manmade (e.g., plutonium).

Radiofrequency power: Electromagentic radiation having frequencies in the radio or microwave portions of the electromagnetic spectrum and extending up to the infrared band.

Radiofrequency (RF) heating: Heating a plasma by depositing radiofrequency power in it. Only radiation at certain specific frequencies—e.g., the electron cyclotron frequency or the ion cyclotron frequency—will be absorbed by the plasma. See "Electron cyclotron resonance heating" or "Ion cyclotron resonance heating."

Radioisotope: A radioactive isotope; in particular, a radioactive isotope of a substance whose naturally occurring isotopes are not radioactive.

Reactive: Able to participate easily in chemical or nuclear reactions.

Reactor potential: A qualitative description of a fusion confinement concept denoting how easy it would be to design, build, operate, and maintain a fusion reactor based on that concept, as well as how acceptable such a reactor's environmental, social, economic, and safety characteristics would be.

Reactor-scale experiment: Experiment to test a confinement concept by generating a plasma equivalent to that needed in a full-scale reactor. Such an experiment must achieve reactor-level values of beta and must demonstrate temperature, density, and confinement times sufficient for the production of net fusion power. Furthermore, its heating, fueling, and other technologies must also be able to support a reactor-level plasma.

Rem: A measure of the effect of radiation on biological systems (acronym for Roentgen equivalent man). Different types of radiation (e.g., alpha particles, beta particles, neutrons, and gamma rays) have different biological effects. Therefore, doses are corrected by a different factor for each type of radiation to convert them into rems. One rem of any type of ionizing radiation produces the same biological effect as one Roentgen of ordinary x-rays.

Remote maintenance: Conducting maintenance on reactor systems or components by remote control, rather than "hands-on." Remote maintenance will be required in fusion reactors and in many future fusion experiments because the radioactivity levels near and inside the plasma chamber will be too high to permit human access.

Resistance: The difficulty with which an electric current passes through a material. For a given amount of electric current, the higher the resistance, the more electrical energy will be dissipated as heat.

Reversed-field pinch: A closed magnetic confinement concept having toroidal and poloidal magnetic fields that are approximately equal in strength, and in which the direction of the toroidal field at the outside of the plasma is opposite from the direction at the plasma center.

Roentgen: A measure of radiation intensity.

Routine release: Releases that occur as a result of normal, or routine, plant operation.

Runaway reaction: A reaction whose rate increases as the power level rises. In such a reaction, any rise in output power increases the reaction rate, boosting the output power still further, and so on. Such a reaction is unstable, growing larger and larger until some other mechanism—e.g., exhaustion of fuel—limits the reaction power.

Scaling: Extension of results or predictions measured or calculated under one set of experimental conditions to another situation having different conditions. One of the most important functions of a confinement experiment is to determine how confinement properties scale with parameters such as device size, magnetic field, plasma current, temperature, and density. It is important to understand the scaling properties of a confinement concept—either empirically or theoretically—to assure that future experiments have a reasonable probability of succeeding.

Scaling relationship: The trend in behavior of a parameter as other parameters are varied. See "Scaling."

Scientific feasibility: The successful completion of experiments that produce high-gain or ignited fusion reactions in the laboratory using a confinement configuration that lends itself to development into a net power producing system.

Self-regulating: A system which, when disturbed in some way, will respond in a manner that tends to compensate for the disturbance. A self-regulating reaction would be the opposite of a runaway one; if the reaction power level were to increase, the system would respond by lowering the reaction rate, permitting the power level to drop back down again. Such a system is also called "stable. See also "Runaway reaction" and "Instabilities."

Shield: A structure interposed between reactor components, such as magnetic field coils, and the fusion plasma to protect the components from the flux of energetic particles produced in the plasma.

Simple magnetic mirror: A magnetic field consisting of a cylinder filled with an axial magnetic field of relatively constant strength, with regions of stronger magnetic field at each end. The stronger field regions tend to "reflect" plasma particles back into the cylinder. However, too many particles nevertheless escape out the ends of the cylinder for the simple mirror to be a viable fusion concept.

Solubility: Ease with which a substance dissolves in another substance.

Spheromak: A magnetic confinement concept in which a large fraction of the confining magnetic fields are generated by currents within the plasma. The spheromak is a form of compact toroid.

Spin: An inherent property possessed by subatomic particles analagous to the rotation of the earth. Just as the spin axis of the earth points towards the North star, the spin axis of a subatomic particle points in some direction. The spin axis of a subatomic particle can be oriented in a particular direction by use of a magnetic field.

Spin polarization: Preparation of many particles, such as deuterium and tritium nuclei, so that their spins point in the same direction. If the spins of deuterium and tritium are polarized, the D-T reaction rate is enhanced.

Spin-offs: The secondary, or auxiliary, benefits of high-technology research and development programs in applications other than those which are the primary motivation for research.

Steady-state operation: Continuous operation, without repeated starting and stopping.

Steam generator and turbine: In an electric generating station, the steam generator uses the heat produced by the power source to boil water into steam, which is passed through a turbine to turn an electrical generator.

Stellarator: A toroidal magnetic confinement device in which the confining magnetic fields are generated entirely by external magnets.

Superconductivity: The total absence of electrical resistance in certain materials under certain conditions. Until recently, superconductivity had only been found to occur in certain materials cooled to within a few degrees of absolute zero. Since late 1986, however, a new class of materials has been discovered that become superconducting at temperatures far higher than the materials previously known. An electrical current that is established in a superconducting material will persist as long as the material remains below its critical temperature. See "Critical temperature."

System studies: Studies presenting preconceptual designs for fusion reactors that serve to uncover potential problems and determine how changes in design choices affect reactor characteristics. System studies are particularly valuable in guiding the reseach program by identifying areas where further research and development can have the greatest impact.

Tandem mirror: Type of open magnetic confinement configuration in which both ends of a simple magnetic mirror, called the central cell, are plugged by end cells to improve confinement. Each end cell is itself a magnetic mirror that generates an electric field to prevent particles in the central cell from escaping. See "Central cell" and "End cell."

Technological feasibility: In this report, acquisition of both sufficient scientific understanding and sufficient engineering and technological capability to design and build a fusion reactor; attainment of both scientific feasibility and engineering feasibility.

Temperature: A measure of the average energy of a system of particles. Given sufficient time and enough interaction among the different portions of any system, all portions will eventually come to the same temperature. In short-lived plasmas, however, the ion and electron temperatures usually differ because of insufficient interaction between the two. Plasma temperatures are measured in units of electron volts, with 1 electron volt equal to 11,605° K.

Thermal instability: Potential instability in a burning plasma arising from the fact that the fusion reaction rate increases strongly with temperature. It is not yet known to what extent burning (ignited) plasmas will be subject to this instability, or whether other, self-regulating aspects of plasma behavior will predominate. See "Runaway reaction."

Thermonuclear fusion: See "Fusion." "Thermonuclear" refers to the extreme temperatures required for the fusion process to take place.

Thermonuclear weapons: Nuclear weapons utilizing the fusion process, also called hydrogen bombs. Thermonuclear weapons are very large-scale examples of the inertial confinement approach to fusion.

Theta pinch: A pulsed device in which a fast-rising, strong (100 kilogauss) magnetic field compresses and heats a plasma column in a few microseconds. The magnetic field is parallel to the axis of a plasma column.

Tokamak: A magnetic confinement concept whose principal confining magnetic field, generated by external magnets, is in the toroidal direction but that also contains a poloidal magnetic field that is generated by electric currents running within the plasma. The tokamak is by far the most developed magnetic confinement concept. See also "Conventional tokamak" or "Advanced tokamak."

Toroidal direction: On a torus, the toroidal direction runs around the torus the long way, in the direction that the tread runs around a tire. More generally, "toroidal" refers to devices in the shape of a torus.

Torus: The shape of a doughnut, automobile tire, and inner tube.

Transformer: Device in which a changing electrical current in one electrical conductor generates a changing magnetic field, which in turn induces electrical current in a second conductor. The plasma current in a conventional tokamak is established by a transformer in which one of the conductors is a set of coils located in the hole in the center of the plasma torus and the second conductor is the plasma itself.

Treaty: The highest level of formality for an international agreement. Treaties involving the United States must be ratified by a two-thirds majority of the U.S. Senate.

Tritium (T or ^{3}H): A radioisotope of hydrogen that has one proton and two neutrons in its nucleus. Tritium occurs only rarely in nature; it is radioactive and has a half-life of 12.3 years. In combination with deuterium, tritium is the most reactive fusion fuel.

Tritium breeding: Production of tritium in the blanket of a fusion reactor by irradiating lithium nuclei with fusion-produced neutrons. Lithium nuclei undergo nuclear reactions with neutrons that yield tritium nuclei and alpha particles.

Turbulence: Random or chaotic flow of a fluid, such as that of water in the rapids of a river.

Umbrella agreement: General agreement between nations establishing a willingness to cooperate in a specific subject area and outlining general procedures, but not specifying particular activities or terms.

Unit rating: The electrical capacity of a generating station.

Uranium (U): A very heavy, radioactive element found in nature that can be used as nuclear fuel. Two uranium isotopes are important in nuclear energy: uranium-235 can undergo nuclear fission, and uranium-238, the most plentiful isotope, can be used to produce plutonium.

Waste handling and disposal: The in-plant handling, on-site disposal (or transportation), and off-site disposal of waste materials formed as byproducts of the energy production processes.

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